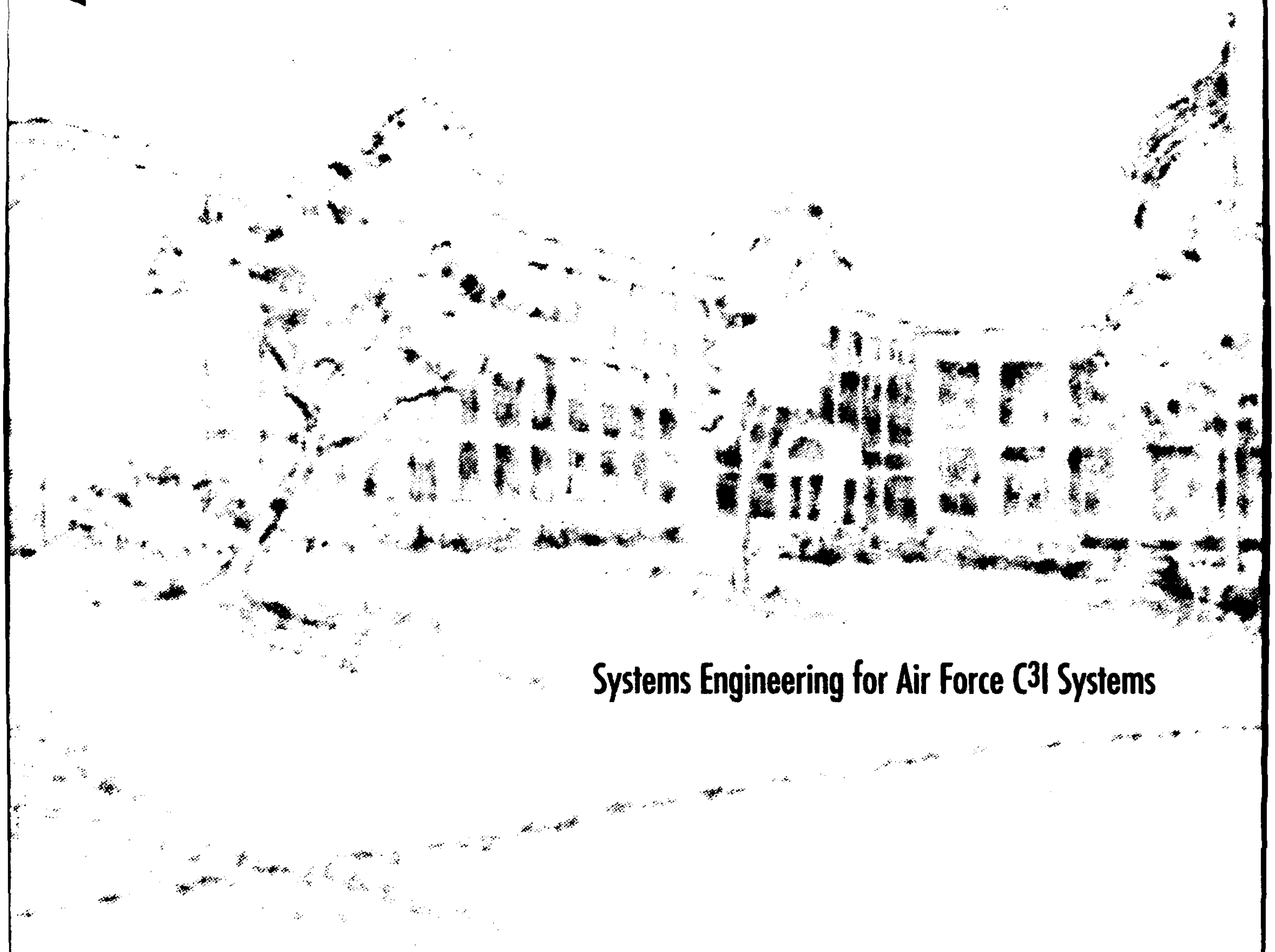

Systems Engineering for Air Force C^3I Systems

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Systems Engineering for Air Force C^3I Systems

John H. Monahan

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MITRE

This book is dedicated to my family—my wife, Barbara, and our children, Susan, Nancy, John, and Amy—in recognition of their love and their support of my work; and also to my colleagues at MITRE, who through their talent and dedication have accomplished so much.

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Foreword

Since 1958, the MITRE Corporation has fulfilled a unique systems engineering role for the United States government. Our purpose is to enhance the nation's security and to otherwise further the public interest through scientific research, support for systems development and acquisition, and technical advisory services. The scope of our activities includes national security matters in the area of command, control, communications, and intelligence (C^3I), as well as civil system areas for the public benefit.

As an independent, not-for-profit corporation, MITRE operates federally funded research and development centers for the Department of Defense and the Federal Aviation Administration. MITRE neither works for nor competes with profit-oriented industry; we often serve as an impartial link between our government sponsors and competitive industry. We strive to bring together the expertise and outlook of government, industry, and academia to solve complex technical problems that cannot be solved by any one group alone.

This book shows the dimension of MITRE's services and the scope of our knowledge as applied to C^3I programs for the Air Force. It provides our employees and sponsors alike with an historical perspective of why the Corporation was formed and describes the breadth and

depth of our role as systems engineer on C^3I acquisition programs. In addition to serving as an overview of some of the Corporation's most challenging work, the book also contains practical advice that can be applied to future systems engineering initiatives. The author—a founder of the Corporation and a knowledgeable systems engineer—played many roles, from project leader for several Air Force-sponsored C^3I programs to Vice President.

Over the last 35 years, MITRE has helped to develop many of the nation's C^3I systems. Our work program evolves continually, according to changes in national needs and priorities. Through our highly competent staff, state-of-the-art facilities, and challenging work program, we uphold our commitment to total quality. And while technology, threats, and national priorities may change, MITRE's commitment to effective systems engineering remains firm. We will continue to apply our technical expertise to C^3I systems throughout the post-Cold War era to the year 2000 and beyond.

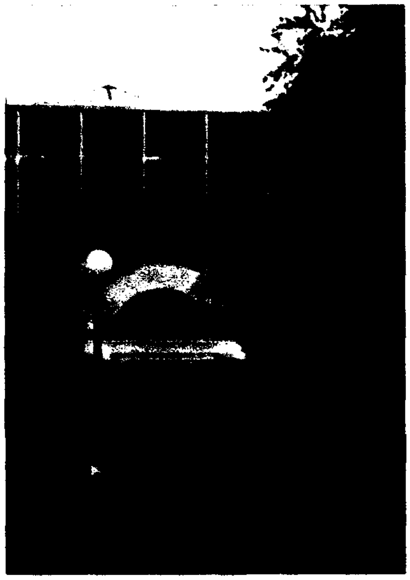
Harold W. Sorenson

Harold W. Sorenson
Bedford Group Vice President
and Air Force FFRDC Director

Acknowledgments

This book could never have been produced if it were not for the extraordinary efforts of so many people who have contributed to MITRE's traditions and accomplishments over the last 35 years. These include MITRE people, of course, as well as government and industry people. They have left a legacy of accomplishments in defense of the country that may never be equaled. They have also left their mark on the field of systems engineering. We are all in their debt.

For the immediate preparation of this material, thanks must go to a number of current and former MITRE technical staff who have supplied material for use in this book or who have generously contributed their time and wisdom to the critical review of the contents. My sincere gratitude extends to each of them. Among this group, I give special thanks to Jack Shay, Sal Pomponi, Hank Therrien, Jack Burke, Gerry Langelier, Bert Fowler, and Charlie Zraket for their extensive review of the early drafts. It was a pleasure to once again interact with them. My special thanks also go to Nancy Dashcund, Linda Scifo, Susan Robertson, and Laurie Wickham in MITRE's Publications Group for their keen interest and professional help in turning the text into a finished product. Finally, my thanks to Dr. Harold Sorenson of MITRE for the opportunity to prepare this, and to him and Don Neuman for their cogent review of the material.



A-Building, MITRE-Bedford

Introduction

Each day, sophisticated information systems provide the U.S. with crucial capabilities both to understand the world situation and to react effectively as required by our nation's decision makers. These systems attest to the success of the cooperative efforts of government and industry. Over the last 35 years, to help provide those capabilities, The MITRE Corporation has been privileged to fulfill the role of systems engineer on more than 100 different command, control, communications, and intelligence (C^3I) systems for the Air Force and other elements of the Department of Defense (DOD). A long history of successful performance in this broad role provides MITRE with detailed knowledge of the systems' operational capabilities and needs, proficiency in their systems engineering, and a C^3I-related corporate memory unmatched by any other organization. That background is the foundation of this book on systems engineering at MITRE.

Chapter 2 describes MITRE's typical systems engineering contributions during all phases of major C^3I acquisition programs. The following chapters summarize the factors that uniquely qualify MITRE for the C^3I systems engineering role and explore some special topics in systems engineering. The material emphasizes the importance of

systems engineering and illustrates approaches and techniques that have proven successful in challenging and high-visibility C^3I programs.

The novice and the experienced systems engineer, as well as others who wish to better understand systems engineering as practiced by MITRE, will benefit from these discussions. There are special insights on how system requirements are established; on interactions among the systems engineer, government, and industry; on being effective in the large, complicated, and volatile environment of a major acquisition program; and on a systems engineering approach to the sophisticated technologies involved in C^3I systems, including risk reduction. Finally, there is a chapter devoted to some special system engineering activities that help transform an idea into a system, and more precisely, one that satisfies the government's requirements at a reasonable cost and on a reasonable schedule, thereby providing an effective, affordable operational capability matched to an important national need.

A large dose of common sense is a very valuable systems engineering tool. One will be surprised at how often common sense seems to be missing.

The details contained in this book derive directly from MITRE's work for the Electronic Systems Center (ESC) of the Air Force Materiel Command (AFMC) and for the predecessors of those organizations, especially the Electronic Systems Division (ESD) of the Air Force Systems Command (AFSC). They reflect MITRE's long and special relationship with ESC, although many of the important considerations discussed also apply to systems engineering work for other government agencies.

MITRE provides systems engineering support to ESC as an essential part of an integrated project team on each program. The emphasis placed on the Corporation's activities should in no way be construed to indicate that MITRE does not appreciate fully the essential roles of government and industry in achieving required system capabilities. The Corporation's role is to work between government and industry as a catalyst, an honest broker, to achieve capabilities. Success depends on a cooperative, mutually respectful, good faith effort by all three parties.

In its systems engineering work, MITRE's main concern is to help customers achieve necessary capabilities on a reasonable schedule and reasonable cost. In a paper on quality assurance at MITRE, president Zraker's foreword notes:

> *. . . success of the MITRE work is explicitly tied to the needs of our clients and to the success that each client achieves in satisfying those needs with development programs acquired at a reasonable cost and on a reasonable schedule. Although MITRE does not have ultimate control of many of the key factors that determine the success of a program, the quality of the MITRE system engineering on a given system is judged, in part, on how well the system satisfied the client's needs.*[1]

It is always a feeling of great pride and satisfaction when the important systems one has worked so hard to perfect perform well in helping to accomplish the operational mission they were designed to support.

MITRE believes a program is a success if the government achieved the best capability possible for the time and money invested. It is always a feeling of great pride and satisfaction when the important systems one has worked so hard to perfect perform well in helping to accomplish the operational mission they were designed to support. MITRE's systems engineering work provides ample opportunity for achieving this professional reward.

Just as in many activities where experience is a key teacher, and especially for those that have some attributes of an art, consummate skill at systems engineering cannot be achieved through study alone. This book provides some help to those involved in systems engineering, but it cannot substitute for actual experience. Likewise, true wisdom often is not fully appreciated until it is personally experienced. The inexperienced systems engineer will find it difficult to relate to the importance of some of the material. Much of it will seem not much more than common sense. It is, indeed, just that. A large dose of common sense is a very valuable systems engineering tool. One will be surprised at how often common sense seems to be missing. In working on an actual acquisition program, the pressures of the moment can make people reluctant to do what seems sensible, especially when that is difficult under existing

[1] *Quality Assurance at MITRE*, Vol. 1, M88-39, The MITRE Corporation, Bedford, MA, October 1988, p. 3.

circumstances. Successfully working through the conflicting demands of high performance on short schedules and at low costs, in an environment where many of the key personalities and controlling factors are constantly changing, is indeed an art. It is best practiced by a skilled, experienced, and dedicated systems engineering team.

For less experienced systems engineers, the material serves as a guide to what is truly important. It provides a useful reference for guidance and resolve when the going gets tough. For experienced systems engineers, this reiteration of what is important will reinforce their determination to do what is necessary, however difficult, to help customers achieve each required capability on a reasonable schedule and at reasonable cost.

The extraordinary systems engineer has the necessary background and knowledge and can apply it without being overly preoccupied by the techniques.

A good systems engineer becomes better through detailed knowledge of both the operational needs and the technologies involved. A systems engineer should have some understanding of the theory of systems engineering and some training in the associated techniques. Also, a systems engineer should be skilled in one or more of the technologies relevant to the systems of interest. This book identifies those attributes that distinguish the exceptional from the ordinary. It focuses on the unique aspects of MITRE's approach to systems engineering. The extraordinary systems engineer has the necessary background and knowledge and can apply it without being overly preoccupied by the techniques. He or she relates well to the environment within which the system is being developed and is dedicated to achieving the required operational mission capability.

At this point, a few words on what is not included are in order. A detailed, step-by-step process for systems engineering goes beyond the scope of this book. MITRE is, however, currently supporting an Air Force effort to more precisely define a systems engineering life cycle flow process to be used in future acquisition programs. In addition, a detailed "how to" primer on each of the many relevant MITRE activities, such as how to write a system specification, or participate in the source selection process, is not included here. Many such papers already exist and are described briefly in the Appendix.

No attempt is made in this material to detail—and certainly not to reform—the DOD approach to the acquisition of C^3I systems. Over the years, many different studies have effected changes to that process. A recent Carnegie Commission study proposes a completely new approach modeled after that used by industry in major commercial development projects.[2] While striving to improve the DOD acquisition process, one important fact must be remembered: through the acquisition efforts of the DOD and the defense industry, there are many very capable military systems operational today. It is not so much the detailed, ideal process that matters, but the experience, skill, and good judgment with which the people involved adapt that process to the particular circumstances and program. This book echoes a sentiment expressed by Arthur D. Hall:

> *I have resisted pandering to a common desire for more treatment of methods or tools, on the ground that sensitivity, knowledge, skill, and good judgment with the process itself are the most important factors in success.*[3]

Systems Engineering—Descriptions and Definitions

> *"When I use a word," Humpty Dumpty said, in a rather scornful tone, "it means what I choose it to mean— neither more nor less."*
>
> *"The question is," said Alice, "whether you can make words mean so many different things."*
>
> *"The question is," said Humpty Dumpty, "which is to be master—that's all."*

Lewis Carroll, *Through the Looking Glass* (from C.D. Flagle, et al.[4])

[2] "A Radical Reform of the Defense Acquisition System," Statement of the Carnegie Commission on Science, Technology, and Government (New York: 1 December 1992).

[3] Arthur D. Hall, *Metasystems Methodology* (New York: Pergamon Press, 1989), p. xiii.

[4] C.D. Flagle, W.H. Huggins, and R.H. Roy, *Operations Research and System Engineering* (Baltimore: The Johns Hopkins Press, 1960), p. 8.

For a term so widely used, there has been relatively little written about systems engineering over the last 30 years. As noted by W.R. Beam,[5] the Library of Congress holdings for 1989 contained only 213 references to systems engineering. A group of books on systems engineering was published in the late 1950s and another group was published in 1989 and 1990, but not much in between. It is interesting that all of these texts refer to "systems engineering," with the exception of R.E. Machol's book,[6] which discusses "system engineering." Both phrases will be used in this book. MITRE's niche is systems engineering, but on any particular program, MITRE is the system engineer in the same way there is a government system program director and, perhaps, a system contractor. Use of the phrase "systems engineering" recognizes the fact that every system the government acquires must interface with many other existing and planned systems. A major concern in MITRE's systems engineering work is the interoperability among all the systems that constitute what is referred to in Chapter 2 as an operational mission capability. In that sense, even on an individual program, MITRE is performing systems engineering.

Most textbooks on systems engineering suggest that the first formal use of the term "system engineering" was by the Bell Telephone Laboratories in the 1940s. The early texts emphasize a multidisciplined team as the essential ingredient of successful systems engineering. They suggest that such an approach was crucial to activities of ancient times, such as the construction of the Egyptian pyramids, and more recent ones, such as the development of television broadcast services. The necessity of a multidisciplined team for many different undertakings—including many outside the field of systems engineering—is almost taken for granted today. Consistent with today's use of integrated product teams, MITRE's approach to systems engineering has always involved project teams consisting of people with

[5] W.R. Beam, *Systems Engineering Architecture and Design* (New York: McGraw-Hill, 1990), p. x.

[6] R.E. Machol, *System Engineering Handbook* (New York: McGraw-Hill, 1965).

expertise in all relevant technologies and in the operational areas that the system is to support.

All the books on systems engineering contain discussions that are relevant to MITRE's work. The material is very lengthy and tends to bury the important points within discussions of disciplines such as operations research, or in component discussions such as computers, radars, or communications devices. However, some quotations from the earlier books help to establish what systems engineering means. They reflect the sort of thinking that pervaded systems engineering at MITRE when the Corporation was formed and remain relevant today.

In 1960, C.D. Flagle et al. noted:

> *System engineering introduces us to a new order of complexity in that a system depends for the performance of its assigned function on the intimate cooperation of a number of devices, each a complicated mechanism in itself. It, therefore, accelerates the obsolescence of the cut and dried empirical methods that formerly characterized all the useful arts and that still play a significant role in them, engineering and medicine not excepted. In systems engineering even more than in other arts, understanding, the product of scientific research, is the catalyst of technological progress. It is essential for survival in a competitive world.*[7]

They go on to observe,

> *The successful system engineer so balances the attributes of discrimination and association that he recognizes real from trivial differences, substantive from illusory resemblances; he is lofty in concept; knowledgeable and wise in selection; critical, alert, and scientifically exact in analysis; and in synthesis, imaginative in plan, meticulous in operation, and practical in execution.*[8]

[7] Flagle, p. 80.

[8] Flagle, p. 80.

They also note,

In particular, it [system engineering] is a field where action must be backed up by scientific understanding—it is too complicated for purely empirical approaches.[9]

As will be discussed in some detail later, MITRE staff must be informed on all matters that potentially impinge on the chances for program success. They must be extremely discriminating in identifying those that are important and in suggesting how they should be handled. To do so requires that the systems engineering team include in-depth expertise on all the relevant disciplines—scientific, engineering and management. And of utmost importance, the MITRE staff must have a genuine understanding of, and appreciation for, the capability that the government user needs.

In his paper published in 1957, E.W. Engstrom wrote:

Inevitably, the proliferation of "black boxes" brought problems of establishing proper interaction among them. Thus, the system engineer began to come into his own, performing the essential task of looking ahead to the ultimate objective—the system—and considering the whole of which each "black box" formed a part.[10]

With this statement of the genesis of systems engineering, Engstrom went on to characterize it in a way that very much applies to MITRE's work today:

As a discipline, the systems approach has these characteristics in all cases, regardless of the great variety of objectives and detailed engineering methods:

1. It is broad in scope, ignoring the boundaries that separate the various academic disciplines, that separate research from engineering, and advanced development from product design and marketing.

---

[9] Flagle, p. 68.

[10] E.W. Engstrom, "System Engineering: A Growing Concept," *Electrical Engineering*, Vol. 76, No. 2, February 1957, p. 113.

2. It is co-operative, usually involving large numbers of people and functions that may appear at first glance to have little to do with one another.

3. It requires compromise, because success in developing a complex system normally involves a sacrifice at one or more points of detail for the sake of the whole system.

4. It is thorough—and by the same token a bit skeptical. The systems engineer must examine every detail that bears upon the function of the complete system. At the same time, he must distrust the tempting "easy" solution that first appears.[11]

Thorough with a dose of skepticism, transcending all relevant factors, and ready to compromise as necessary to achieve the necessary system capability—this characterizes well the challenge faced by MITRE in its systems engineering tasks.

A review of the literature provides many different definitions of system and system engineering. For example, R.E. Machol offers several different definitions of each as gathered from other texts on the subject.[12] They range from mathematical set-theoretic definitions to rather simplistic ones. DOD documentation defines system engineering as

the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives.[13]

[11] E.W. Engstrom, pp. 113-114.

[12] R.E. Machol, *System Engineering Handbook* (New York: McGraw-Hill, 1965), pp. 1-12.

[13] *Engineering Management*, DOD MIL-STD-499A, May 1974.

Alternatively, the Defense System Management College offers the following:

Systems engineering is the management function which controls the total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness.[14]

One sample of the definitions used by industry is this one from IBM, in which system engineering is

the iterative but controlled process in which user needs are understood and evolved through increasingly detailed levels of requirements specification and system design to an operational system; includes the intellectual control and integration of all disciplines throughout the system life cycle in a manner so as to ensure that all user requirements are satisfied.[15]

MITRE has no corporate definition of systems engineering, and this book will not provide one. Some will be disappointed at that, but brief definitions inadequately convey the breadth and depth of the systems engineering activities performed by MITRE. On the other hand, MITRE has been instrumental in developing many of the concepts that have become an integral part of systems engineering as it is practiced today, both at MITRE and at other organizations. Many of them are discussed in detail later. From the beginning, MITRE recognized that the systems engineer must actively participate in system design evaluation, and conduct necessary design verification activities.[16] Other innovative concepts include the use of the system itself to monitor its own performance,[17] and to provide for operator training. MITRE also recognized the need for a

[14] *System Engineering Management Guide*, Defense System Management College, January 1990.

[15] *System Engineering Principles and Practices*, IBM Federal Systems Division, Bethesda, MD, June 1983.

[16] J.W. Shay, *MITRE System Engineering Book Outline*, W-07353/0000/01, The MITRE Corporation, Bedford, MA, 1964.

[17] J.H. Monahan, *Quality Control in SAGE*, TM-3012, The MITRE Corporation, Bedford, MA, 1961.

Jack Jacobs and Bob Everett, MITRE Systems Engineering Pioneers

system to continue to operate in degraded conditions resulting from enemy action or from internal system failures. The use of live exercises for system evaluation and the appropriate use of simulation tools for estimating system performance were early MITRE initiatives.[18]

The phased implementation of systems such as the Semi-Automatic Ground Environment (SAGE) system and the 425L NORAD Command Operations Center in the late 1950s and early 1960s is an early example of a MITRE approach that was later adopted by the acquisition community at large and referred to as evolutionary development or preplanned product improvement. The utility of an operational employment plan in managing a successful acquisition program was a MITRE initiative.

As another example of MITRE's contribution to the art of systems engineering, consider the following. In a speech to the Operations Research Society in 1961, John F. Jacobs of MITRE identified the

[18] J.F. Jacobs, *Practical Evaluation of Command and Control Systems*, MTP-7, The MITRE Corporation, Bedford, MA, November 1965.

hierarchy of design within which a system must be considered and discussed the component, subsystem, and system levels.[19] Beyond that, he explicitly recognized that each system being acquired is imbedded in successively higher level systems that address individual mission capabilities, overall military systems, and ultimately national systems that transcend even those overall systems. For example, a radar might be considered a component of an air defense system, air defense part of the nation's defense system, which in turn is part of the Joint Chiefs of Staff's managed military system. That system then must operate within a national system that includes others such as the air traffic control system. Expanded versions of these concepts were presented by Jacobs to the Air Staff in June 1962[20] and again in 1963.[21]

In 1976, another MITRE paper written by Jacobs described the concept of a "system-of-systems."[22] This concept explicitly recognizes that each system being acquired must interoperate with others at parallel or lower levels, and that the collection of such systems is, in turn, embedded in other systems of greater scope. At that time, some people even used the term "super system engineer" to describe the Air Force's need for systems engineering—not just system engineering—because most operational mission capabilities actually consist of many different subcapabilities, each of which is accomplished by an individual system.

The remainder of this book addresses the specific MITRE activities that constitute its role as systems engineer on a major Air Force C^3I system acquisition program. All are important, even if some of them lie outside a precise definition of systems engineering. When the term "systems engineering" is used here, it is meant to include all of them.

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[19] J.F. Jacobs, *Air Force Command and Control System Development*, SR-23, The MITRE Corporation, Bedford, MA, July 1961.

[20] J.F. Jacobs, *The Integration and Standardization of Automated Information Systems*, SR-68, The MITRE Corporation, Bedford, MA, August 1962.

[21] J.F. Jacobs, *Military Information Systems*, SR-92, The MITRE Corporation, Bedford, MA, August 1963.

[22] J.F. Jacobs, *System Architecture and System-of-Systems*, M76-206, The MITRE Corporation, Bedford, MA, June 1976.

As systems engineer, MITRE must be cognizant of a range of factors that transcend the strictly technical. These factors are continuously assessed to determine whether they indicate that some action should be taken to improve the chances of achieving the needed capability on a reasonable schedule and at reasonable cost. When MITRE project personnel recognize that something must be done, it is incumbent on them to work with the government program director and the integrated product team to make sure that appropriate action is taken.

There is no inference that the implied definition of systems engineering at MITRE would apply anywhere else, in government or in industry. Neither is it meant to imply that MITRE does all the systems engineering on programs for which it is assigned the systems engineering role. Indeed, many of the government and industry activities on a program are substantial, and may properly be referred to as systems engineering.

MITRE's Ron Grimm Aboard Joint STARS During Desert Storm

MITRE's Role in Acquisition Programs

As systems engineer on a C³I system acquisition program, MITRE makes major contributions in each of the typical program phases from initial conception, through acquisition, to the full operation of the system by the using command. MITRE's role, responsibilities and products in each phase are the subjects of this chapter. This chapter also poses the key questions that must be answered and discusses MITRE's work in helping to answer them. In addition, it describes the value MITRE adds in the systems engineering role.

Phases of an Acquisition Program

Understanding the major program phases through which each new DOD acquisition program moves is helpful as background for the discussions of MITRE's contributions. This section describes each phase and the critical times when decisions must be made before entering the next phase. Over time this process has changed, and it will continue to evolve as government and industry work to improve the acquisition process.

As described in *Program Baselines and Milestones*[23] and more recently in *Defense Acquisition Management Policies and Procedures*,[24] in a classic acquisition program the government recognizes an operational need and studies potential alternative systems that might provide the required capability. If the need is ratified and one or more of the alternative systems is judged responsive to the need, affordable, and obtainable on the required schedule, the system is approved for a phase in which industry is given a contract to build this system. The first major phase, Phase 0, is one in which needs are assessed, alternative system solutions studied, and decisions made on whether to proceed with actual procurement. To describe this phase further, there is a decision point known as Milestone 0 at which a proposed program need is approved or disapproved for entry into the next sequential activity, Concept Exploration and Definition. Some of the factors considered include alternative programs, associated costs and schedules, long-term affordability (sometimes referred to as life-cycle cost) and the proposed acquisition strategy. At the end of that phase, the program reaches Milestone I. Then, the program is evaluated to determine whether to proceed to the next step in the acquisition process, the Demonstration and Validation phase. This is also referred to as Phase I. In Phase I, risk reduction efforts are performed, critical technologies demonstrated, and refined performance objectives, system concepts, costs, and schedules developed.

After completing the Demonstration and Validation phase, the Milestone II decision determines whether to proceed into full-scale system development. If approved, the program enters Phase II, Engineering and Manufacturing Development. In this phase, profit-making industry that may have been involved in the earlier studies and analyses builds the development system. The Milestone II decision might also include approval for low-rate production of the proposed system to verify that the contractor has the knowledge and facilities

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[23] *Program Baselines and Milestones*, Defense Systems Management College, No. 1.12, December 1988.

[24] *Defense Acquisition Management Policies and Procedures*, Department of Defense Instruction No. 5000.2, February, 1991.

for full-scale production of many systems. It is one challenge to build a single copy of a system that performs acceptably; it is quite another to effectively replicate the system many times, as is often the requirement in C³I programs.

At Milestone III, the government reviews what was accomplished during the development phase and decides whether to proceed into Phase III, Production and Deployment, in which full production and initial deployment to the forces that will operate the system take place. In addition to the results of the development program, other factors considered include a current estimate of the threat, probable production and life-cycle costs, likely schedules, reliability and maintainability, logistics supportability, producibility, and many others.

When the production system is built and tested to demonstrate that the contractor provided the system promised in its contract, the program moves into a government operational test and evaluation period in which the system's operational effectiveness is assessed. Phase IV, Operations and Support, overlaps Phase III. After the system has been in operation for some time, and on an as-required basis, a Milestone IV decision may occur. At that time, the necessity for a major system upgrade is reviewed. If one is approved, and on an as-required basis, changes are made to those systems that are still in production. Major changes to the systems that have been already been produced by the time of Milestone IV compete with other possible alternatives in a new Phase 0.

Before describing MITRE's systems engineering activities in each phase of a C³I system acquisition program, there is one note of caution. The above description should not lull anyone into believing that the acquisition process is as straightforward as it is represented here. As discussed in Chapter 3, the acquisition environment is much more complicated than the ideal described.

Corporate Role and Responsibilities

MITRE's role is to help the government achieve required capabilities. In that role, the Corporation often participates in studies and analyses leading to the establishment of an acquisition program,

performs as the system engineer during the acquisition, and participates in the evaluation of system performance after the system becomes operational. The involvement from early conceptual studies through acquisition and system operation provides MITRE with unique insight into the government's operational requirements and the performance that is achieved in field operation. Understanding the requirements helps in making judgments and recommendations as systems engineer. Observing actual system performance is an important foundation for subsequent analysis of future government needs. A history of having performed successfully in this broad role on Air Force C^3I systems for over 35 years provides MITRE with in-depth knowledge of operational needs, systems engineering skill, and a corporate memory unmatched by any other organization.

Airborne Battlefield Command and Control Center in Flight

This chapter summarizes the types of MITRE activities that may occur prior to the establishment of an acquisition program by the government. The Corporation's activities in each of the acquisition program phases are reviewed and its work in helping to evaluate the performance of the operational system is described. Although no step-by-step prescription is provided, important activities are identified, crucial questions to be answered are posed, and some cautions and suggestions are discussed.

The chapter is organized by discrete acquisition program phase. However, in reality, programs are often in several different phases at the same time. For example, at any time, there is an existing operational capability on which the new acquisition program will be based. While a new capability is in development and test, the next generation of that capability may be in early conceptual planning. The evolutionary nature of C^3I and other systems is an important consideration in planning for operational capabilities and in carrying out the associated acquisition programs. Even though the section emphasizes activities characteristic of a new acquisition program, it should be noted that most MITRE work involves systems engineering for major additions to existing capabilities. The additions are acquired by the same program office that acquired the original capability, and the Corporation normally continues as systems engineer throughout the program.

Conceptual Planning

A quotation from Shakespeare, as noted by A.D. Hall, helps to characterize conceptual planning for new systems.[25]

When first we mean to build,
We first survey the plot, then draw a model;
And when we see the figure of the house,
Then we must rate the cost of erection;
Which if we find outweighs ability,
What we do we then but draw anew the model
In fewer offices, or at least desist
To build at all?

Shakespeare, *King Henry IV, Part 2*, Act 1, Scene 3, Line 4

Many activities, sometimes over a number of years, precede the government's establishment of a new acquisition program or a major initiative under an existing program. The first impetus to establish a new program may come from a newly perceived user requirement, change in enemy threat, availability of more capable technology, or an opportunity to achieve required system performance at substantially

[25] A.D. Hall, *Metasystems Methodology* (Elmsford, New York: Pergamon Press, 1989) p. 7.

lower costs. Suggestions for possible acquisition programs may come from any sector of government and industry, including MITRE. However, the user community, in conjunction with the DOD, in the end establishes the requirements in any given case. The DOD and Congress provide for the establishment and funding of an acquisition program. What constitutes a system requirement and how one is established deserve further elaboration here.

Just as there is no universally accepted definition of "system" or "system engineering" in the C^3I acquisition business, there is no unanimity of opinion on what level of information constitutes a legitimate description of a user requirement. Some people suggest that the use of the word "requirement" is harmful because it tends to connote something that is inviolate, even when circumstances dictate that it is no longer practical or necessary. Everyone would agree that a requirements statement such as "defend the United States" is an inadequate prescription to permit a responsive system to be built. At the other end of the spectrum, most would also agree that it is inappropriate for a user requirements statement to specifically identify the hardware to be acquired.

In a paper on defense planning, General Glenn Kent (U.S. Air Force retired) suggests that it may be legitimate to say there is a requirement to increase the nation's capability to achieve some operational objective. He notes that one should be careful in suggesting that there is a requirement to achieve some particular operational task. He then goes on to state, "We should not say that we have a requirement for a particular weapon or system, and, then, we have a requirement for certain performance features in that system." As examples of what is meant by "operational objective" and by "operational task," General Kent describes preventing the Soviet Union from dominating Western Europe as a national objective that involves strategies, such as providing a robust forward defense with conventional forces. This strategy in turn, he notes, might involve operational objectives, such as delaying/damaging of Soviet follow-on forces. That objective could involve a number of tasks, such as damaging bridges. General Kent suggests that

it may be appropriate to refer to "requirements" down to the operational task level, but not beyond that, into the realm of systems, subsystems, and hardware.[26] That is, General Kent believes it may be appropriate to establish a requirement for destroying bridges, but not for specifically how that will be done. He also states that choosing among the alternative ways to achieve a national objective, i.e., among operational objectives, requires study of the effectiveness and cost of doing the tasks implied by the operational objective. That in turn requires analysis of the alternative systems that might help perform the various tasks.

The effectiveness and cost studies implied in choosing among operational objectives and in selecting systems to perform those tasks, require the technical expertise of the development community.

The effectiveness and cost studies implied in choosing among operational objectives and in selecting systems to perform those tasks, require the technical expertise of the development community. In particular, MITRE has an important role to play in these activities.

In this book, the word "capability" is used interchangeably with the phrases "mission capability" or "mission system capability." They are meant to be equivalent to General Kent's "operational objective." The individual system that results from an acquisition program is not necessarily a capability, as the word is used here.

Many parts of the government and nongovernment groups contribute to the process of establishing system requirements. By actively participating in the analysis of alternative operational objectives and tasks, MITRE can help to establish meaningful and feasible requirements. However, in the end, the ultimate using command, in conjunction with its service and DOD headquarters, establishes the requirements for any particular acquisition program. The development agencies then must satisfy those requirements, although funding and scheduling constraints may result in continuing reassessment of the requirements.

Experience indicates that there are few absolutes in the establishment of user requirements for capabilities that are to be satisfied by the acquisition of a large, complicated command and control system. One might imagine that users know exactly what capability

[26] G.A. Kent, *A Framework for Defense Planning*, R-3721-AF/OSD, Rand Corporation, Santa Monica, CA, August 1989.

they wish to achieve and can describe it succinctly to the agency assigned to provide it to them. The real-life situation is considerably different. In a recent book on systems engineering, Beam makes the following comments on the process by which user requirements are established:

> *System requirements may emerge from a user organization, but even here they may represent the unresolved views of a group of individuals. Even at best, users are generally not certain just what they really need. This is especially true if (a) they have had no experience with similar systems, and (b) no such systems are currently available. Thus:*
>
> - *Requirements will in most cases be fragmentary, at least in some respects.*
> - *Requirements will usually address high-level systems needs, but key requirements may be omitted from attention.*
> - *System requirements are often overstated, beyond actual needs, because special groups of users pose their own requirements independently without overall control within the user organization.*
> - *Fine detail requirements are often included among true top-level ones.*
> - *Seldom are requirements prioritized; users are always hopeful that they will achieve every need or wish.*
> - *It is not uncommon to find sets of inconsistent requirements for any large or complex system.*
> - *Some requirements may be given whether really needed or not, and some may be given merely because it has become traditional to ask for them. This is often true where there are documented standards, since naming a standard document is often simpler than deciding what is truly required.*[27]

[27] W.R. Beam, *Systems Engineering Architecture and Design* (New York: McGraw-Hill, 1990), p. 54.

A using command is made of many different people with different and valid concerns—operations, maintenance, personnel, training, and logistics. There is great variety in the experience of these people and in the relevance of that experience to the particular acquisition being planned. Most of them have challenging, full-time jobs associated with carrying out the current mission of the command, and those jobs take priority. Describing a new capability is not an easy thing to do. Evaluating alternative operational objectives and tasks is time-consuming and demands considerable technical expertise. It is especially difficult to communicate user requirements to people in the development community who do not have the same experience and understanding as the user. With little time to think about it, and in many cases, with limited directly applicable operational experience, it is understandable that some user representatives have difficulty in describing the desired capabilities to development agencies. It should also not come as any surprise that different levels within an operating command may have different priorities among various requirements, or indeed, very different requirements. In particular, a commander is apt to have much greater insight into the command's most urgent needs, and much more conviction on how those needs should be fulfilled, than people at lower levels in the using organization.

To complicate matters, proposed requirements for a new capability must also be reviewed and approved by higher headquarters within the user command service, negotiated with the other services with which the capability interacts, and DOD must agree with them and approve their funding. Congress and the congressional staff are often involved in establishing and reviewing a program. Getting agreement is not easy. Compromise is necessary and the potential implications on the subsequent acquisition program are often very significant.

The system acquisition process used by the government also complicates the process of establishing requirements and inhibits effective achievement of required mission system capabilities. In the late 1950s and early 1960s, the agencies responsible for acquisition programs, known as system programs offices (SPOs), had broader responsibili-

ties than they typically do today. The SAGE SPO was responsible for acquiring all continental air defense system sensors, communications, and control centers, and for ensuring that they interfaced properly with the weapons systems acquired separately by other Air Force and Army program offices. The 407L Tactical Air Control SPO had similar responsibility for the Air Force's tactical air control system. MITRE's first system engineering job was for SAGE; the Corporation also had system engineering responsibility for 407L. Over time, the approach of using "basket SPOs" fell into disfavor as the resulting programs became very large and costly, and those unfamiliar with program details found it difficult to determine what was actually being done and how well.

As an alternative to the basket SPO approach for developing system capabilities such as air defense, tactical air operations, or finding and killing ground targets, the capabilities were broken down further into their major subsystems; these subsystems were acquired by separate government program offices. With this change, a government program director was assigned the job of buying a radar, or a piece of communications equipment, or an operations center. Direction for each program tended to become very bounded: do precisely this, in this much time and for this much money. The program direction, time, and money rarely provided for the activities to interface the various subsystems. No real attention was given in the individual acquisition programs to making sure that all the activities would converge in a way that would provide the overall mission capability that the users demanded.

What was intended as a good business practice actually introduced serious problems into the process of achieving a capability. In this paper, a radar is not a mission capability—or as used here—not a capability. In the language of this book, the government began a process of buying subsystems. To achieve an operational mission capability, each subsystem has to interoperate with other existing and planned subsystems, and the entire complement of subsystems must be orchestrated by available operating and maintenance personnel.

ESD, Spanish Air Force, and MITRE Coordinate on Combat Grande

The new acquisition approach tended to delay recognition of important interactions among the subsystems until they began field operation. Of course, the user community properly complained when they did not get the capability they needed. In some cases, acquisition programs were deemed failures when in part the problem was a result of the acquisition process itself. A user/developer tension in the acquisition process developed and remains a cause of some of the problems that still beset C^3I acquisition programs today. Users try to specify technical solutions; developers question operational needs. Both sides need to do a better job in their own domains.

In many cases today, there is no overall architect for development of a mission capability. In effect, the problem of assembling the various acquired pieces into a mission capability is left as an exercise to the ultimate using command, often without access to the technical resources required to do so. Each contractor is obligated to deliver the subsystem described in the contract, each program director to deliver the subsystem described in the program direction. Certainly, both groups feel a responsibility to see to it that their particular piece fits into the mission capability. However, neither has the responsibility, experience, or resources to ensure that a mission capability is achieved. MITRE, however, does have some of the experience necessary to address the programs in terms of a mission capability. Interestingly enough, the change in acquisition approach increased the

government's need for a group with the experience and knowledge to help discrete subsystems function together as capabilities. In this sense, the new acquisition approach increased the government's reliance on MITRE, and the challenge was entirely consistent with the Corporation's role and objectives.

As noted above, MITRE's first job was to help the Air Force achieve a continental air defense capability. MITRE has had systems engineering responsibility for many of the C^3I related subsystems that are essential to the user's capabilities. In many mission areas, the Corporation has had that responsibility for over 35 years. MITRE therefore has the inclination, detailed knowledge, and experience necessary to assume a broader role in helping the ultimate user achieve the required capabilities. With the necessary knowledge comes both opportunity and responsibility. Long experience with mission capabilities is one of the essential factors that helps define the uniqueness of MITRE. Again, however, the opportunity reflects itself in a responsibility to help each customer achieve the required capability. This responsibility is recognized and welcomed by the Corporation. It is taken seriously by the staff and management.

The using command has the ultimate responsibility for achieving the required operational mission capability. The command must define what it needs, participate actively in the process of establishing and completing the necessary acquisition programs, accept the new systems and combine them with existing systems, and provide the personnel and training to operate the systems. Much has been written about the need for user participation in C^3I acquisition programs if they are to be successful. Their participation is certainly required. Users know in general what they need, and they have to make the subsystems into capabilities. The more they know about what they are getting, the better. In the rush to apply this wisdom to the acquisition process, some misjudgments have been made.

A true development activity cannot be accomplished by the using agency, since it does not have the required resources. On the other hand, it is important that the agency be involved to help shape the

resulting capability and to help in the transition from development to operational use. Development must be done where the development talent exists, not necessarily at a user headquarters. Ideally, the user will provide personnel at the optimum development location to achieve the necessary user participation. Again, ideally, these user personnel will move into the operational locations as the newly developed system moves into field operation. Programs have failed for lack of adequate user participation. However, they have also failed when they were attempted at user locations and adequate development resources were not brought to bear on the scene. As in most other considerations, each acquisition program must plan for proper user and developer participation. There are no fixed rules, except that both groups must be properly represented, or failure or disappointment with the resulting capability is likely.

Requirements are not chiseled in stone and handed down from the mountain. Even when approved requirements statements are available, they leave much room for interpretation.

As the earlier quotation from Beam makes clear, requirements are not chiseled in stone and handed down from the mountain. Even when approved requirements statements are available, they leave much room for interpretation. It is MITRE's task as systems engineer to take those operational requirements and translate them into technical performance requirements. That process results in a technical specification that is used by the SPO to hire a contractor to build the required subsystem in such a way that when it is combined with other subsystems, it will provide the user command with the required capability. For that to happen successfully, the Corporation must understand not only the requirements associated with the current program, but how the resulting system fits into the overall mission system capability.

As part of the process of establishing requirements, MITRE has a responsibility to state what is technically feasible within the constraints that may apply to the program, such as available time and money. The Corporation often has experience relevant to the capability in question, and based on that experience should propose achievable system requirements. In addition, it should comment on what others may propose as system requirements. MITRE's considerations

should include technical feasibility, associated risk, likely cost and schedule, impact on or by other programs, and alternative requirements. Although not often discussed, in the requirements formulation stage MITRE can have a significant impact on the capability that is eventually achieved. The Corporation needs to be proactive in this stage, not merely reactive.

As with everything else in the acquisition of major system capabilities, over the course of the program, there will be changes proposed in the operational requirements. A change in threat or user employment plans may occur. Changes may even be proposed by MITRE. Often, people or organizations will attempt to get the program director to agree to these changes without going through any formal approval process. If the change is significant—that is, if it affects performance, cost, or schedule in ways that significantly increase the risk of successful completion of the program—MITRE should recognize that fact. In turn, the Corporation should strongly urge the system program director who manages the SPO to defer from making the change until it is formally approved, and until the resources necessary to accomplish it are provided. MITRE should help the program director to estimate the performance, time, and cost implications of the proposed changes. These implications should be made known to both the user community and to those who provide the funding for the acquisition program. By clearly identifying the implications, this approach will weed out those changes in which the user command is not seriously interested. It will also eliminate those for which adequate funding and time have not been provided to the development command.

Occasionally, a user command will desire a new capability but reject the approach suggested for achieving it. For many years, the predecessors of the Federal Aviation Agency performed air traffic control using raw, or video, radar information. When capacity and accuracy requirements for air traffic control dictated the application of computers, it was necessary to digitize the video information so it could be processed by computers. However, the controller agency was comfortable with the use of video and concerned that the

digitizing process might eliminate the display of certain aircraft, even though video was present. As a result, for several years, both the video and processed radar information had to be displayed to air traffic controllers. The processed data was provided to achieve the increased system performance that the air traffic situation demanded and that the government required. The display of video was maintained in the new system until controllers were convinced, by the system performance, of the validity of processed radar data as a basis for a safe air traffic control system. Such problems are not unique to air traffic control. The use of digital data communications in place of voice has been resisted by some factions of the military on similar grounds. As was done in the air traffic control case, the design of the new capability must accommodate these very real considerations, and MITRE must be especially sensitive to them.

Other unusual requirements problems may arise at any time in a program. In Southeast Asia, there was a system that controlled rescue flights over North Vietnam in attempts to retrieve downed airmen. When the losses on those flights rose to unacceptable levels, the Commanding General of the 7th Air Force instituted a requirement that he personally approve each flight. These were very important missions and also among the most dangerous. The Commanding General wished to personally judge the likelihood of success in each case and to weigh that against the potential for further losses. To provide him with detailed information at his headquarters location, the system involved was quickly modified.

The last example is reminiscent of a general problem that always exists in establishing requirements for a new system. What decisions will be made at each operating level within the using command? How much of all the information available within the system will be provided to each command level? If all information is available at all levels, the higher levels may be overwhelmed by too much data. Or, the lower levels may be uneasy that higher levels, especially those outside their service command, may usurp their functions. If too little data is provided to higher levels, important decisions may be made

erroneously. This is another area in which MITRE's experience on earlier versions of the system, or on other related systems, may be quite helpful in recommending a sensible distribution of functions and information. Perhaps the system design needs to be flexible, allowing for alternative operations as the situation may dictate.

In establishing system requirements, the user command must also describe any differences between those of peace and war. In peace, the cost of operation is always a major consideration, but less so in war, when effectiveness transcends other factors. A system may not have a day-to-day function except during war, yet it must be available on short notice, personnel must be trained, and it must operate reliably. One thought that has been impressed on MITRE by military commanders over the years is that one cannot expect to use a system in a certain way during peace, and then be successful at operating it differently during war. Capacities may be different in peace, or some additional checks required before taking action, but fundamental system operation must be the same.

What does this all mean to MITRE as systems engineer for the proposed acquisition program? One of the main points of this book is that to be effective in the systems engineering role, MITRE personnel must have a genuine understanding of, and to the extent possible, a real experience with the capability that the system is to provide.

To be effective in the systems engineering role, MITRE personnel must have a genuine understanding of, and to the extent possible, a real experience with the capability that the system is to provide.

Of all the qualities and capabilities that MITRE brings to the acquisition of command and control systems, this appreciation for the capabilities desired by the government is uniquely MITRE's. What it means for MITRE to understand the desired capability, how that understanding is acquired, and how it is applied in any particular acquisition program are detailed in Chapter 4.

Complicated though the process may be, the government has many mechanisms to study the effectiveness of the various military capabilities and to evaluate potential improvements. Existing systems are subject to daily use. Special operational exercises and tests are conducted to help evaluate system performance in ways not stressed by day-to-day operation. New systems go through development testing and readiness testing

before becoming operational. All of these activities help to establish the level of performance of the existing capabilities and provide indications of where improvements may be necessary. Beyond that, the Air Force and the other services fund mission system planning activities to study new potential system capabilities, including considerations of technology, operations, and costs. On occasion, the Air Force establishes and funds conceptual planning studies at MITRE. For major upgrades to existing systems on which MITRE has the systems engineering role, it is quite common for MITRE to do the conceptual planning for the upgrade as part of the funded systems engineering work.

In addition to the resources available within the operating and development communities, the government employs a variety of other groups to help evaluate current performance and to study potential new systems. These include, for example, the Defense Science Board and the Air Force Scientific Advisory Board. If appropriate, help may be enlisted from other groups, such as the National Academy of Sciences, which are less directly involved in DOD matters. Special ad hoc groups may be set up to study important problems. More than one of these groups may examine a new technology for potential applications or a critical operational need for possible technical solutions. In doing so, they interact extensively with the development and operational communities.

The MITRE technical staff has been privileged for many years to participate in a wide range of these activities both as a part of the development community and as contributors to the special government studies performed by groups such as those just mentioned. In the early 1960s, MITRE staff helped the Air Force evaluate alternatives for survivable continental air defense systems that led to the acquisition of the Backup Interceptor Control (BUIC) air defense system. The Corporation was an important part of the studies that led to a series of acquisition programs for upgrading the ability of Air Force C^3I systems to support tactical mission operations anywhere in the world. MITRE has performed similar work in strategic mission areas such as missile warning and space defense. In some cases, the

government has funded the Corporation to perform the separate studies; in other instances, MITRE staff members have participated as members of Air Force or other study groups. MITRE and industry studies, together with Air Force-funded advanced development programs conducted by the Corporation, led to the establishment of the Joint Tactical Information Distribution (JTIDS) program. Similar MITRE work helped the Air Force achieve the Have Quick voice radio antijam capability.

MITRE staff members have participated in external studies conducted by the Defense Science Board and many other special study groups. The subjects to which MITRE personnel have contributed range over areas such as ground target surveillance and attack, C^3I systems countermeasures and counter-countermeasures, C^3I systems for next-generation ballistic missiles, survivable communications, supportability of U.S. mission system capabilities, and the Strategic Defense Initiative (SDI). The combination of in-depth technical knowledge and understanding of the operational missions found in the Corporation's technical staff has resulted in it being requested to participate in these studies. That combination has also helped the staff to make significant contributions to the results. In return, the MITRE staff has learned much from the experience and has established important relationships in government, academia, and industry. The knowledge and rapport gained are important to the effectiveness of the Corporation's systems engineering work.

As one might infer from the material just presented, conceptual planning for a new system, or for a major addition to an existing system, is not always a bounded, well-disciplined process. Many voices have to be heard. Needs may spring from the user community. System ideas may be proposed by industry, MITRE, academia, or any of the many study groups. Industry or academia may offer technology without knowing where it might best be applied. Criticism of current capabilities may come from any quarter and may be legitimate or biased, knowledgeable or emotional. In this sort of environment, MITRE must be mindful of its role—to help the government achieve

required capabilities on reasonable schedules and at reasonable costs. Objective, informed assessment of all relevant factors must be the basis for MITRE's recommendations on how best to satisfy the government's needs. MITRE must be prepared to defend its recommendations in both government and other forums.

With some knowledge of what may be desirable and what may be possible to do, MITRE hypothesizes broad alternative system designs. Each design is studied for likely system performance and assessment of inherent risks. System and support costs and schedules are estimated. The potential threat and the environment in which the system must be approved, developed, and operated are factored into the concept, schedules, and costs. MITRE's work is subject to scrutiny by others within the acquisition community, as well as by various study groups, and often by industry. The risks are evaluated by the Corporation through further analysis or experimentation.

As results are determined and comments received from other parties, the Corporation refines the alternative system approaches and adjusts the estimates of performance, risk, schedule, and cost. MITRE provides the results to the government, along with recommendations on how to proceed. MITRE is prepared to participate in the deliberations at that time in any way deemed helpful by the government. The Corporation is eager to be an active participant because it feels it has something substantive to contribute to the decision-making process, and because the insight provided by direct participation is especially helpful in understanding the government's decisions and in carrying them out when MITRE is assigned the systems engineering role. MITRE's active participation is important both to the Corporation and to the government. With care on both sides, it can be accomplished without any real or apparent compromise or abrogation of the government's ultimate responsibility for making the decisions about what will or will not be acquired and how.

In many cases, there are substantial predetermined constraints that must be respected in any concept planning or concept definition activity. In one example, MITRE was asked to define alternative

systems for improved survivability of the continental air defense system, but the total cost could not exceed $100 million. In ancther instance, an interface capability was required between two tactical systems, but it had to be operational in less than a year. Meeting the requirements was possible in both of these cases. However, if too many of the attributes of performance, schedule, or cost are fixed a priori, the possible system solutions may be seriously constrained. It is conceivable that meeting all the constraints is undesirable or even impossible. In such cases, MITRE must be prepared to recommend how best to compromise among the factors driving what can be done, or even to recommend that the program should not proceed under the given circumstances.

Whenever a conceptual study of a potential new system or capability is undertaken, MITRE must have discussions with all the key players. This includes those involved in the study, the using command, others who may participate in approving the system for acquisition or in developing it, those whose expertise may contribute to a successful program, and any factions that are likely to dissent. Only in that way will MITRE obtain a true picture of the government's needs and constraints, what may or may not be possible, and the environment surrounding the potential system. As has been observed, two of the attitudes that distinguish MITRE's approach to systems engineering are in-depth understanding of the operational requirements and familiarity with the total environment within which system acquisition and operation take place. The Corporation's recommendations are only as good as its staff's knowledge of both these factors and the technologies involved in accommodating them.

The key questions that MITRE should help to answer in the concept definition phase include the following: What is the proposed operational capability? What are some of the alternate levels of capability? What are the different approaches to achieving them? What are the schedule and cost implications of each? What are the associated risks? What actions should be initiated to reduce the risks to acceptable levels? What areas need special attention during acquisition?

Who has strong opinions? How may they affect the program? What should be done to mitigate their concerns or correct any of their misconceptions? What is happening in other related programs that may impinge on the capability? How will developing technology affect future capabilities in this area? Is it timely to proceed now or would it be prudent to delay the program for some time?

In summary, MITRE can assume a very important role in helping the government to analyze alternatives and establish system requirements. The Corporation has much relevant experience, understanding, and information—about both the operational capabilities and the technologies—that can be helpful to those who are responsible for deciding the requirements for a particular system. The Corporation is responsible for providing that background throughout the life of an acquisition program, especially in the phase when the initial requirements are being established.

Activities Preceding Industry Solicitation

When the government decides to acquire a new capability, it publishes a program management directive (PMD) outlining the nature of the capability to be acquired and describing the constraints under which it is to be acquired. For example, the PMD identifies the available funds. Quite often, the capability reflected in the PMD varies from those proposed in the concept design alternatives. In that case, further study and analysis must be done by MITRE to help determine how best to carry out the program direction. Clarification and modification of program direction may be required to ensure a good foundation for the program. MITRE should work as part of the SPO team to obtain them.

Sometimes the PMD is assigned to the system program director of an existing SPO. Where there is no appropriate SPO, a new one is created. In either case, the program director hires MITRE as systems engineer when the Corporation is the best source of that support.

MITRE makes one of its most important contributions in the period between the government's decision to acquire a system and the

time that industry proposals to build it are solicited. In that period, the Corporation prepares the system specification that will be used as the basis for soliciting the industry proposals. The specification will also be used in subsequent programs phases as a benchmark for assessing the progress of the program. MITRE also participates in other pre-contract solicitation activities, including helping to prepare the operational employment plan and the acquisition strategy.

The Operational Employment Plan

When the dust has settled on all the "what ifs" studied in the concept definition phase, it is a worthwhile exercise to generate a plan to describe how the user intends to employ the system that has been approved and funded for acquisition. Historically, such a plan was often generated on ESC-developed systems. It is strongly recommended that such a plan be generated for all new systems. In the past, the plan was referred to as an operational employment plan, or OEP. The utility of such a document is becoming more widely recognized. For example, the Air Force Ballistic Missile Organization has published a draft preparation guide for a Baseline Concept/System Description document.[28] As described in the draft guide, this document is similar to, but somewhat more narrow in scope than the OEPs produced on ESC programs.

The OEP may be written by the using command or it may be a product of a combined user-developer group. Very often, MITRE's understanding of both the operational needs and the associated technologies permit the Corporation to make significant contributions to the OEP. In many ways, by publishing the OEP, the using command is saying, "If you build me a system that meets the requirements of this plan, then you will have satisfied my requirements." Such a statement is beneficial for understanding among parties. It is a statement that will either survive the key personnel changes that take place during a program or provide a basis for equitably negotiating change.

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[28] *Baseline Concept/System Description Document Preparation Guide*, Draft, Ballistic Missile Organization, Norton Air Force Base, CA, May 1992.

In the OEP, the using command interprets, in operational terms, what it believes has been approved for acquisition. The document states how the command intends to employ and support the new capability, and how it will interoperate with the other existing and planned portions of their mission capability. It is an opportunity for a close dialog between user and developer to resolve any last minute confusion over what is desired and what will be delivered, before industry is put on contract to build it. The OEP is also a governor on future changes that may be required by the user or on future disputes about what was done versus what was supposed to have been done. Future needs may be justifiably different. Good management requires that the foundation for the program be described and agreed to by the user and developer. Changes can then be accommodated by changing the agreement. This approach provides a businesslike basis for renegotiating the resources available to the developer for achieving the revised capability.

Since the OEP is normally published by the using command, it is a command-level statement of requirements, rather than merely a statement by one or more command personnel. As such, it stands the test of time more adequately. That is especially important in future negotiations of program change. If events are such that changes in operational requirements dictate modifications to the system, the OEP provides a basis for negotiating them. The OEP agreement also helps to define the test programs that will be conducted as part of the acquisition program to demonstrate that the system works as planned and that resulting capability is operationally acceptable. Since expectations and people change as time passes, the OEP improves the ability of the participants to manage more equitably the impact of change on the required test programs.

By participating actively in the OEP process, MITRE gains insight into what the user wants in the capability. In turn, that insight is valuable to the Corporation's work in preparing the system specification used in soliciting industry. MITRE can also help improve the user's understanding of the capability to be provided and the risks

associated with trying to do so. The key questions associated with the OEP phase are: Is there a good understanding between the user and the developer on what is required and how it will be provided? Does it reflect the program direction? Is the understanding sufficient to proceed with the program?

Acquisition Strategy

When a decision is made to acquire a new capability and a PMD is issued to initiate the program, a system program director is also appointed to manage the acquisition. Some years ago, the phrase "acquisition strategy" was invented to cover a myriad of decisions that the program director must make in establishing the acquisition approach to be followed. The program director is not a completely free agent in this process. Many of his or her decisions are subject to review by higher headquarters and to coordination with other participants, such as the using command and the various commands responsible for training, construction, and logistics. Sometimes, direction given to the program director specifies in part how the acquisition will be managed.

The acquisition strategy for a program may include many different factors. Will there be a prime or system contractor? If not, how will the capability be broken into pieces that can be contracted for separately? What form will the contract take, fixed price or other? Will contract incentives be used? Will the capability be provided in incremental steps? Will there be a study phase before actual development? How will the contractor be selected?

In discussing acquisition strategy here, two points are emphasized. The decisions made in this phase are critical factors in the success or failure of the program. Experience clearly shows that good decisions facilitate a successful program and that poor ones are a prescription for trouble and, in some cases, failure in the acquisition program. The second point is, as systems engineer, MITRE must take the initiative to actively participate in the decisions concerning acquisition strategy. The Corporation has the benefit of experience with the approaches that did

or did not work on similar past programs. In addition, many of the questions to be answered in establishing the acquisition strategy have significant technical components that must be considered. For example, in this phase of a program, MITRE has a greater understanding of the amount of development that will be required than any other program participant. This knowledge should be brought to bear on decisions, such as the need for system studies or development models and even the contract form to be used. As systems engineer, MITRE must take a very active approach to understanding the key issues on the program and to providing appropriate recommendations to the program director on the acquisition strategy to be employed.

Certain management approaches have tended to be in vogue at different times. For example, there have been times when the preferred acquisition approach was to hire a prime or a system contractor and to make that contractor responsible for providing the total system. At other times, conventional wisdom dictated that the government would achieve more for its money if, for example, it hired the best hardware contractor and then separately contracted with the best software firm. A third contractor might be hired to integrate the efforts of the first two, or the government might assume that role with assistance from MITRE. Selecting the approach to be used is an important choice, and each alternative has associated pros and cons. Often, the choice has extremely important technical ramifications, and the Corporation's expertise can help highlight the risks and advantages of the available alternatives. For example, in a case where the hardware and the operational software are to be procured separately, one must take great care in deciding which contractor will provide the support software, such as the operating system. That is a difficult decision, one that can make or break the program, and one that is in large measure driven by technical factors on which MITRE has considerable expertise and experience.

As in all matters associated with the acquisition of large and complicated C^3I systems, there is no universally optimum prescription. Each instance has to be evaluated on its own merits. Some failures in

acquisition programs can be traced directly to acquisition strategies inappropriate for the program at hand. Having a single system contractor significantly reduces the negotiations the SPO must conduct with industry. A single contractor may give the SPO more flexibility in managing tradeoffs between the various subsystems that constitute the capability. With a cooperative system contractor there is increased flexibility; with a reluctant one, there is less.

The need to accommodate change is omnipresent in the acquisition of large C^3I systems. A cooperative, skilled system contractor improves the chances for accommodating change with least possible overall impact on the program. An uncooperative or unskilled system contractor can make change a very difficult and costly process. One might be concerned that when there is a system contractor, the SPO has no alternative but to make any necessary changes through that contractor. Knowing that, the contractor may suggest high costs for any change. On the other hand, the government has perfectly adequate mechanisms for negotiating "should cost" in a reasonable way. The system contractor may make changes internal to the system that the government does not like while still claiming to deliver the overall capability. For example, the system contractor may decide for business reasons to take work away from an important, skilled subcontractor and move it into his own organization.

In all these cases, MITRE can make valuable assessments of the technical ramifications of the contractor's actions. The Corporation is able to make estimates of the work involved in a change and therefore can help calibrate the cost and schedule impacts of the changes. MITRE's work on technical, cost, and schedule impacts helps provide the SPO with substantive information as a basis for government evaluation of the contractor actions.

When there is no system contractor, the government must either do the work required to integrate the pieces itself or hire another contractor to do so. The government is very short of the professional resources necessary to perform integration functions. Hiring an integration contractor introduces an industrial component that has no control over the

contractors building the subsystems, requires bringing that contractor up to speed on the capabilities required and the technology involved, and requires the government to be prepared to referee disputes that will inevitably take place between the various industrial corporations. Some critics claim the activity is an unnecessary overhead placed on top of the contractors providing the subsystems. When MITRE was first formed, the number of systems being procured was small and the Corporation was able to assist the government by performing in the system integrator role. Today, MITRE continues to provide significant support in this area, but limitations on technical staff availability preclude the possibility of the Corporation assuming total integration responsibility in all but the most special circumstances.

Whether there is a system contractor or not, the program director and MITRE must appreciate that if the acquisition program fails in some important way, they will be held responsible.

Although some people may disagree, it seems clear that when in doubt, the best approach is to hire a system contractor. Care must be taken to select one that has demonstrated competence in the type of system being acquired and has the necessary resources available for assignment to the program. The contractual arrangements with the system contractor must be such that the SPO remains in charge of its destiny, retains the necessary visibility into the system contractor's activities, and is not completely at the mercy of the contractor management when changes are necessary. It is particularly important that there is adequate visibility into the activities of the subcontractors so that MITRE has the information required to provide technical assessments of program status and to help in evaluating changes initiated by the contractor or the government.

Whether there is a system contractor or not, the program director and MITRE must appreciate that if the acquisition program fails in some important way, they will be held responsible. If the program does not provide the required operational capability, both MITRE and the government, as well as the contractor, have failed. When there is a system contractor, the Corporation must continue to do everything it normally does to help the government acquire the required capability. When there is not, MITRE must also be prepared to help the government provide the necessary integration functions.

Another aspect of acquisition strategy involves creating as much industrial competition as possible. The more qualified bidders there are, the more likely that innovative approaches will be proposed and that systems costs will be as low as practical. Competitive study contracts are sometimes employed as part of the acquisition strategy. Such studies provide the government information on how a capability might be achieved, possible levels of performance, risk areas, and associated costs and schedules. They help identify strengths and weaknesses among the participating contractors. The contractors learn more about the capability required and how it may be provided. Often, the alternatives studied involve competing state-of-the-art technologies. Direct participation by MITRE helps guide the contractors to examine the most critical design and performance questions. The Corporation's expertise in modern technologies is available to help evaluate the results and quantify the probable cost and schedule impacts of various approaches suggested by the contractors. The Corporation also can help apply the results to the subsequent acquisition program by including appropriate information in the MITRE-prepared system specification. The information gained is also useful in the technical evaluation of the contractor system acquisition proposals, and in the evaluation of contractor progress as the program proceeds.

On the other hand, if improperly used, study contracts can be a waste of the government's time and money. To the extent possible, the study contractors should be corporations that are capable of participating in the actual development of the system. If possible, contractors solicited for developing the system should be limited to those who executed the study contracts. At a minimum, the results of the studies should be applied to the acquisition program. As discussed in some detail in the section on system design, there is often great reluctance about giving design direction to an acquisition contractor. This reluctance should not keep the government from making maximum use of the study results in the acquisition program.

In almost every acquisition program, some portion of the capability will be provided by industry and some portion by the government. Even when there is a system contractor responsible for delivering a total system capability, one finds that some piece of the necessary test equipment is government-furnished or some existing operational equipment must be provided to the contractor for integration into the total system. Or perhaps the government is responsible for providing the facilities in which the system will be installed. Whatever the specifics, government-furnished equipment (GFE) or facilities are an important consideration in the formulation of the acquisition strategy. MITRE must help the SPO identify both what is required and who in the government will provide it. This activity has a significant technical component that the Corporation can help to provide. For interfacing systems, what are the electrical characteristics that must be matched? What message standards will be employed? What changes may be taking place in either system that might affect the interface? The Corporation's experience with a wide variety of C^3I systems can be very helpful in identifying the questions that must be answered and in providing answers that can be used by the contractor and by the government to ensure a successful operating interface. The availability of electrical power, air conditioning, and long range communications are other areas that often require MITRE technical contributions to ensure that the new system will operate successfully when delivered by the contractor.

Negotiations to provide for GFE or facilities must be completed and subsequently monitored for timely implementation. One must also be concerned about the characteristics and the operating condition of the GFE to be turned over to the contractor. The contract must include that information and provide for demonstrating that the equipment is indeed in the prescribed condition. Failure to meet the government's commitments with respect to GFE may cause serious delays in the contractor's work and attendant cost increases to the government.

As noted earlier in this book, C^3I systems evolve over time in response to changes in requirements and in available technology.

New capabilities are defined, acquired, and implemented as the need arises. However, there is another basis for evolutionary development that is more predictable; it is sometimes referred to as preplanned product improvement. This is not a new notion, despite what some may think. When the SAGE air defense system was conceived in the 1950s, it was recognized that new sensor and weapon system developments were in progress and that they would have to be incorporated into the SAGE system. It was also recognized that the threat was evolving in ways that would provide much faster enemy bombers than those that existed at the time SAGE was first built. The acquisition approach adopted was to build the system in models, with model 2 replacing model 1, model 3 replacing model 2, etc. That way, an early capability was achieved, advanced planning for major additions to the system was accomplished, and a sensible approach to acquiring them was established. Major additions after initial operation included the frequency diversity radars, the century series interceptors, a capability to track supersonic aircraft, the BOMARC and NIKE surface-to-air missiles and the airborne long range radar input (ALRI) system.

The emphasis on acquiring subsystems, as opposed to capabilities, that one finds in today's approach to system acquisition makes broad use of preplanned evolutionary development and acquisition more difficult. Because MITRE has a role in so many of the C^3I subsystems purchased by the government, the Corporation has a special responsibility for ensuring that the subsystems may be effectively combined to achieve the required capability. As discussed above, MITRE's expertise on the technical characteristics of C^3I systems can be applied to minimize problems between interfacing systems.

Beyond that, even in individual acquisition programs, there are important considerations of evolutionary development. One need only examine the history of the Airborne Warning and Control System (AWACS) program to appreciate the number of important additions to the system's capability that have occurred over the reasonably short life of that program. Again, there are important technical considerations that MITRE can help identify and evaluate.

Knowing that future additions will be made, perhaps one should purchase more computer capacity than is required for the first increment of capability, thereby avoiding a costly future computer retrofit. Or perhaps the software architecture can be partitioned to facilitate future known additions.[29] It is important for MITRE to consider such alternatives as part of its work in the precontractual phase of the acquisition program, and to provide its assessments to the SPO in a timely fashion.

Development implies uncertainty and uncertainty in any dimension implies uncertainty in cost. A fixed-price contract may limit the government's cost exposure but may provide less performance than required.

As another consideration in helping to map the acquisition strategy of a new program, MITRE must consider evolutionary development and make recommendations for its application. Perhaps one piece of the capability will take considerably longer than others. Maybe a useful capability can be achieved significantly earlier if a phased implementation is employed. This is another important area in which the Corporation's knowledge and experience can help make an important contribution to a successful program.

Another aspect of acquisition strategy concerns the type of contract to be employed. Again, one approach may go in and out of fashion as people change or as the community struggles with how to improve the acquisition process. Contract type is indeed an important choice, but it is not a panacea. First, one must remember that the objective is achieving the required capability. If one saves a great deal of money but does not get the capability, the program has failed. Beyond that, contract type does not even guarantee that money will be saved. A few observations relevant to contract type can be made. They grow out of MITRE's experience across many C^3I system acquisitions. First, true development efforts cannot be accomplished for a fixed price. By its nature, development implies uncertainty and uncertainty in any dimension implies uncertainty in cost. One may use a fixed price contract to limit the government's cost exposure, but in that case, one has to be prepared to live with a product that may provide less performance than required.

[29] B.H. Horowitz, *The Importance of Architecture in DOD Software*, M91-35, The MITRE Corporation, Bedford, MA, July 1991.

Incentive contracting is another approach frequently used. The contractor is given special incentives to contain the cost by being required to pay for any cost overruns but allowed to share in any cost underruns. The contractor may receive extra fee if the required performance is exceeded or be penalized if it falls short. Alternatively, the fee may be varied as a function of the government's judgment of contractor performance—the so-called award fee. Experience indicates that such incentives may work, but they also may be ineffective or even counterproductive. When the contractor has signed up for too low a price, a cost incentive may detract from performance. The trouble is that the incentives may not represent the major drivers that govern the conduct of the contractor. Other important factors may include reputation, establishing the corporation in a new business area, deferring profit to a subsequent program phase, and the desire to hold a team together or to keep a facility open. However, the most important point is that the use of incentive contracts does not relieve either MITRE or the government from the responsibilities to carefully monitor program progress and to actively pursue any changes deemed necessary. Contract type is never an acceptable substitute for good management.

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In formulating the acquisition strategy a few other concerns should be addressed. Multiple concurrent development contracts should be avoided. Often, they will get out of synchronization in both time and performance, will cost time and money, and may require a compromise in the achieved capability. It will create a management problem in resolving which contract should be modified and how. For example, it is highly risky to undertake a software development effort until the computer on which the software will operate has completed development.

One final comment on acquisition strategy is appropriate. The approach should not demand too much too early. The front end of the program should provide time for the contractor to gain a good understanding of the requirements, do the necessary system design work, and get agreement with the government on the design approach. Inadequate time up front will cause pressures that lead to bad decisions. Everyone will want to maintain the schedule. As an

example, when schedules are tight, some people will want to proceed with coding the computer programs, even though the design is incomplete. If properly used, adequate time spent at the beginning will result in substantial savings later in the program. MITRE should work to ensure that the acquisition program does not demand too much too early. The staff should then work with the government and the contractor to ensure effective use of the time provided.

The key questions to be asked in reviewing the proposed system acquisition strategy are: Does the strategy accurately reflect the state of development as it applies to the desired capability? Is the implied distribution of responsibilities among the contractor, government, and MITRE optimum for achieving the required capability? Are the time and money allotted consistent with the effort to be accomplished? Does the plan provide for adequate access to the contractor information necessary for effective government program management?

System Design and Specification

The most important paper produced by MITRE in the system engineering role is the system specification. This document is an essential part of the procurement package used to solicit industry proposals. In large measure, the industry responses are evaluated in terms of their responsiveness to the MITRE specification. Throughout the development program, the specification is used as a guide against which to make judgments on progress or to evaluate proposed changes. The specification describes the minimum essential technical requirements and sets the boundaries for the system to be acquired. As with the other subjects discussed herein, this section does not attempt to provide a step-by-step description on how to write a system specification. Instead, the material describes the role of the system specification and identifies some of the major factors that must be considered by MITRE in preparing it. Other MITRE documents discuss the preparation of a system specification.[30,31]

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[30] R.S. Nielsen, *A Purposeful Specification*, WP 3750, The MITRE Corporation, Bedford, MA, 1971.

[31] J.W. Armstrong, *Some Guidelines for Writing Military Specifications*, WP 20726, The MITRE Corporation, Bedford, MA, 1976.

MITRE staff must keep one ultimate objective in mind when preparing the system specification: an operational system that satisfies the government's needs. In effect, when MITRE prepares a system specification and provides it to the government, the Corporation is saying: If the system satisfies the specification, it will meet the government's stated operational requirements. Although not explicitly expressed in this way, the system specification carries with it a MITRE guarantee of this form. When approved by the many government agencies that review it, the specification becomes the technical yardstick against which contractors are selected and future progress is measured. After preparing the system specification, MITRE's system engineering responsibility then consists of helping the government, in every way possible, to acquire a system that satisfies the requirements established in the approved system specification.

If the system satisfies the specification, it will meet the government's stated operational requirements.

One aspect of the system specification coordination process deserves special mention here. In their book on systems engineering, C.D. Flagle et al. note,

> *A new scientific hypothesis or discovery is considered valid only after it has been subjected to scrutiny and after its truth has been verified. A new design, however, is seldom exposed to such treatment. Since the design is more of an art than it is a science, its evaluation by others tends to be subjective.*[32]

This quote is especially true in the stage when the system specification is under review. MITRE must be prepared to defend its choice of technical requirements by being able to tie them back to operational requirements and by whatever analysis and experimentation may be necessary to provide evidence of their validity.

The process involved in starting a program to acquire a new operational mission capability, or to make a major addition to an existing one, can be long and tortuous. That process may delay the needed capability for years. Naturally enough, once an acquisition program is finally approved, there is a great interest on all sides in achieving

[32] C.D. Flagle, W.H. Huggins, and R.H. Roy, *Operations Research and System Engineering* (Baltimore: The Johns Hopkins Press), 1960, p. 107.

the required capability as soon as possible. Everyone wants to get the procurement package together and hire the contractor to build the system. However, at the front end of the program, one must spend the time and money necessary to provide a solid foundation in requirements, technical approach, acquisition strategy, and schedule and cost estimates. Judgments are required on how much is enough, and MITRE must be prepared to provide the SPO with advice in these areas—both to help ensure that what is prudent to do is accomplished and to help avoid unnecessary delays or expenditures. To avoid unnecessary delay after a program is approved, and assuming the necessary resources can be made available, uncertainties and risk areas should be pursued during the period in which the government is deciding whether to proceed with the system.

Competitive industry develops outstanding technology applicable to C^3I systems. On the other hand, the government is not seeking innovation in every dimension of a new capability. The government does not need it and cannot afford it.

Competitive industry develops outstanding technology applicable to C^3I systems. The acquisition process must provide for appropriately applying that technology. On the other hand, the government is not seeking innovation in every dimension of a new capability. The government does not need it and cannot afford it. After building systems of a certain kind for a number of years, one begins to understand what level of performance in certain functions is adequate to support required operational capabilities, even when those capabilities have to be extended to some degree. That is, in some cases, the government and MITRE understand the performance that a certain design can achieve and have established that level of performance as adequate for the capability intended for acquisition. To give an example, consider the design of the computer program that accepts radar data and uses it to establish and follow aircraft tracks. This function is referred to as automatic tracking. A tracking system design that provides adequate performance for a certain class of systems has existed for over 25 years. Systems using that design have operated very successfully for many years. However, since system design is the responsibility of industry, the government does not prescribe design information as part of the specification provided to industry in soliciting industry bids.

At the same time, the acquisition community recognizes that pertinent design information, often developed for the government at considerable expense, should be made available to the industry for its use in building systems that operate as required and are affordable both in their acquisition and operating costs. Over time, alternative approaches have been developed to provide design information to industry without including it in the system specification and, therefore, without requiring that it be applied to the new system being acquired. Strawman designs developed in feasibility studies by MITRE or industry can be made available for information purposes in a library accessible to all potential bidders. Some information may be included in the formal bid package for information only in "notes to the specification." Information exchange meetings can take place prior to the formal bidding period. To ensure that industry has appropriate design approaches, the bid package may require that the industry response include feasibility designs for critical areas.

On the matter of design versus performance information, the approach MITRE must follow is clear. Minimally acceptable performance requirements must be included in the specification because they tell all parties what must be achieved. At the same time, the Corporation must acquire or develop enough design level information to establish system feasibility and to successfully estimate potential system costs and schedules. The Corporation should then work with the SPO team to make appropriate portions of this information available to industry in ways that neither stifle industry initiative nor open the government to undue risk. That risk is a double-edged sword. The government wishes to minimize the risk of system failure and therefore has an incentive to provide all the information it has to the industry. The government also wishes to avoid the risk of future claims that design information provided by the government was faulty. For any particular system, there will be a tradeoff in these two objectives, and the amount of design information provided to the industry will revolve around the depth of the government's experience in an area and the extent to which the new system requires significant increases in the state of the art.

Obviously, MITRE has neither the knowledge nor the resources to specify a complete design in sufficient detail for the contractor to build the system without going through another design phase. That is, MITRE is not in the business of providing "build-to" specifications for C^3I systems. As in so many areas of systems engineering, informed judgments must be made by MITRE in recommending how much design information to provide to industry. As noted by W.R. Beam,

> *The most successful system designers usually create designs evolved from proven architectural approaches rather than seeking change for the sake of change.*[33]

When a function is very critical and a working design is known, the design should be provided. When certain design approaches are known to be flawed, they should be ruled out. Every good engineer likes to design. MITRE staff must control that appetite and restrict their inclusion of design approaches to those known as critical to system performance and to those well-proven in comparable systems. Even when design approaches are provided in a bid package, the proposal evaluation process must allow for industry to submit alternative designs if they can demonstrate they are substantially better in performance or lower in cost.

Of course, MITRE must also avoid "goldplating" either the system requirements or the system design. Again, quoting Beam,

> *The novice system designer may be worried if a requirement does not address all design-decision topics. The well-qualified system designer views overrequirement as an evil and welcomes those that permit maximum leeway in the design. If the requirements appear to be delineated either through insufficient or overrequirement, the experienced designer will take steps to understand the needs of the user(s) and establish priorities.*[34]

[33] W.R. Beam, *Systems Engineering Architecture and Design* (New York: McGraw-Hill, 1990) p. 86.

[34] Beam, p. 54.

Too much or too little in either requirements or design approach leads to systems that fail to provide the required capability or that do so only after unreasonable delays and expenditures. Analogously, MITRE must avoid the premature application of technology in preparing the system specification and must help the government preclude industry attempts to introduce it when the risks or the costs associated with it are unnecessary.

In establishing proposed technical requirements, MITRE must focus on those user requirements that have been most clearly identified. One should avoid including requirements just because they were part of an earlier system. Requirements for "off-the-shelf," "modular," and other like slogans must be used with great care. They should not be invoked unless they can clearly be satisfied. Wholesale application of military specifications (MILSPECS) is expensive and may be counterproductive. MITRE must be conversant with the details of these specifications and apply them selectively and sparingly in consonance with what is really necessary to ensure achieving required system performance. The Corporation must be prepared to defend those choices against others who will want to err on the conservative side by more widely invoking these MILSPECS.

MITRE must avoid the premature application of technology in preparing the system specification and must help the government preclude industry attempts to introduce it when the risks or costs are unnecessary.

MITRE must be concerned with how the system to be acquired will interact with other existing and planned systems. An overall architecture must be developed and kept in mind as the system specification is prepared. W.R. Beam characterizes the desired architecture as follows:

> *The author believes that an expertly architected system stands out from the ordinary, in certain characteristic ways. These are often readily discerned, even by diligent students of system architecture:*
>
> *It evidences an overall unity—its parts do not compete but complement one another, and are similar in quality, durability, and utility.*

It has no parts that appear to be afterthoughts. Likewise, there is little waste in its operation, no duplication of parts except that required to fulfill functional, performance, or reliability objectives.

It exhibits balance, order, symmetry from many points of view: e.g., internally (through its structure and organization), externally (through its appearance and ease of access and use), logically (through design relationships), and functionally (through economy of design, meeting the objectives without waste).

It has not only a sound top-level scheme but its quality holds up in detail as well—close examination of its parts reveals the same qualities and soundness as does the system as a whole.[35]

The various subsystems that compromise the total system must be identified as part of the system specification and incorporated in the MITRE proof-of-concept design work discussed below. Each of the system functions must be distributed to the subsystems and allotted among hardware, software, and operating personnel. One must avoid optimization at the functional or subsystem level; it is total system performance that matters. And it is not just the C^3I system level either, but rather the operational mission level, such as described earlier in this book.

In considering the overall architecture, MITRE must identify, isolate, and control key risk areas. Some will be technical in nature, others will be management-oriented. If the efforts of other organizations are necessary to enable a successful program, MITRE must identify them and work as part of the SPO team to secure the necessary commitments from those organizations. During the program, MITRE must help monitor whether those commitments are being satisfied in a timely way and apprise the program director accordingly.

For technical risks, MITRE must undertake risk reduction efforts. In some cases, the Corporation should recommend industry, academia, or

[35] Beam, p. 86.

government initiatives to reduce the risk. These activities may be part of the development contract or they may be accomplished under separate contracts before initiating the formal acquisition program. Risk reduction analyses and experimentation may also be conducted by MITRE. In any case, the results should be reflected in the system specification. As a rule, if one knows how to reduce important risks, the approach should be specified. Any significant residual risk in performance, schedule, or cost should be taken into account by tailoring the acquisition strategy, as discussed in the previous section.

One important question that MITRE must answer in preparing the system specification is whether there is a conceivable, implementable system design that would satisfy the performance requirements established in the specification. Having outlined the performance requirements, MITRE must examine them and postulate an initial system design to meet them. This was referred to above as a proof-of-concept design. It is a reasonableness test of the technical performance requirements. It helps to identify risk areas, which should be studied as early as possible. The requirements should be steered in the direction of lowest risk.

Like technical risks, high cost functions must be examined closely to be sure they reflect important requirements and that the approach to achieving them is a good balance between what is needed and what it costs.

Identification of major cost drivers is another important product of initial MITRE design efforts. Pre-acquisition contract work by MITRE or by industry may be necessary to establish ways of accomplishing the required functions at lower costs. The high cost of certain functions may result in a reexamination of the system requirements. Cost considerations could dictate a change in the distribution of functions among the hardware and software components of the system, or that some functions planned for support by the data processor are best accomplished by the system operators. Like technical risks, high cost functions must be examined closely to be sure they reflect important requirements and that the approach to achieving them is a good balance between what is needed and what it costs.

Since a C^3I system will evolve and may have to operate for many years into the future, growth provisions are another concern to be addressed in the system specification. Again, informed judgment is

required to provide prudent growth capability without unduly increasing the cost of the initial system acquisition. In addition to growth, one might provide the necessary interfaces to accommodate other systems that will follow in development.

Considerations of the human operator are another very important factor in initial system specification and design work. The distribution of functions among the operators and the system hardware and software is critical. Operators must remain in control of the system. At the same time, operator reaction times should not seriously degrade system performance. One should be careful to avoid underestimating what the operating personnel can contribute to a successful system. Placing too much reliance on the automated portion of the system can be very costly. The burden of tedious, repetitive, and boring tasks should not be placed on the operators. At the other extreme, one cannot demand that all the operators be the equivalent of Ph.Ds. Careful consideration should also be given to how the operators will work with one another. Whenever people are involved, special care must be given to life support functions. All of these matters have to be addressed as part of preparing the system specification. References to MITRE documentation relevant to the user interface design may be found in the Appendix.

In the process of preparing the system specification, MITRE will identify a number of requirements for the system being acquired to interface with other existing or planned systems. The number of these interfaces can be very large. For example, a system such as AWACS must interface with many different U.S. and allied ground C^3I systems. It also must interface with many different aircraft and with Navy surface ships. The interface characteristics of any new system must be specified. Typically, MITRE must also be prepared to monitor the evolution of interfacing systems to ensure that when changes are made in other systems they are reflected in the system being acquired and for which the Corporation has systems engineering responsibility. In some cases, the new system requirements and the initial design will suggest that changes should be made in one or

more of the interfacing systems. MITRE must identify those instances and work with the SPO to get them negotiated with, and implemented by, those responsible for the other systems.

Another key aspect of MITRE's work in preparing the system specification concerns how one can measure progress toward satisfying the requirements of the system specification and in turn demonstrate that the required system capability has been achieved. Quality assurance provisions must be included in the system specification. They include requirements for system performance data recording, data reduction, and analysis capabilities. The testing provisions of the system specification are further detailed in other documentation, as discussed in the Operational Testing section.

Some key questions must be answered during the preparation and coordination of the system specification. Does the specification describe a system that will satisfy the stated user requirements? Do all parties agree on that? Can the technical requirements in the system specification be traced back to the user's operational requirements? Have the major risks been identified? Have they been reduced to acceptable levels, or is there a plan to do so? Is there at least one system design that matches the specification requirements and can be built by industry within the cost and schedule constraints? Have all the actions that must be taken by the government to complement the industry work been identified?

Request for Proposal Package

The package of material sent to industry in selecting a contractor to design and build a new system is known as a request for proposal, or RFP. In cases where MITRE is the system engineer, the RFP package contains the MITRE-prepared system specification as a major ingredient. The specification describes the technical performance requirements for the system. However, the RFP contains a number of other important documents and the Corporation plays a significant role in generating some of them. These include the statement of work (SOW), instructions to the bidders, contract data requirements list

(CDRL), and perhaps others, such as the listing of government-furnished support resources.

As the pieces of the RFP package are prepared, a draft version should be made available by the government to industry in some way that shows no bias toward any particular contractor. For example, they can be made available in a library that contractors may visit with the understanding that it is for information purposes only and that the draft documents are subject to change before final publication.

In preparing the RFP, one should attempt to minimize the number of options that a contractor must provide. They are expensive to generate and difficult to evaluate. Another area that should be watched closely is the requirement for the contractor to submit documentation to the government. Documentation is very expensive to produce initially and very costly to review by the government and maintain by the contractor. Documentation requirements should be kept to a minimum. Every document required should have a clear and necessary purpose.

The government's commitments on the program must be accurately described and the responsible agencies clearly identified. The government's intentions for the various test phases must be enumerated, and procedures for retesting and for change control should be included.

The plans by which the source selection will be conducted should be provided and evaluation criteria identified. If specific data or demonstrations or sample systems are required, they must be carefully described and their role in the evaluation process discussed.

Many sections of the RFP will be prepared by the government itself. MITRE prepares the system specification and helps with many of the other sections. As system engineer, the Corporation must review the entire RFP package to ensure that it describes the capability the government requires, its provisions are internally consistent, and it provides a reasonable basis for contractor selection and subsequent system development. The key questions to be answered are embodied in these considerations.

Proposal Evaluation

MITRE has published an excellent document on the source selection process, corporate policies and procedures relating to the participation of personnel in that process, and the attendant ethical considerations and issues.[36] Suffice it to say that source selections are very important government responsibilities. MITRE must be vigilant in all it does to avoid any action that would compromise, or appear to compromise, that process. The Corporation's credibility in the systems engineering role for the government is dependent on unbiased and professional conduct by all its personnel.

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Since there is such an excellent reference, there is no need in this book to discuss MITRE's activities leading up to the source selection, or those that take place during the evaluation of contractor proposals and contract award. It should be noted, however, that MITRE does not vote on which contractor should be awarded the contract. The Corporation does provide an evaluation of all contractor technical proposals against the requirements of the MITRE system specification included in the RFP package. Also, although MITRE does not have access to the contractor's cost proposals, MITRE staff assigned to the source selection team do provide evaluations of the amount of effort estimated by a contractor to complete a given technical task. It takes a technical person to know how much effort a technical task is apt to require.

In helping the government formulate the RFP package and evaluate contractor responses, MITRE should search for ways that will most readily indicate the contractor's understanding of the work to be done. They should be included in the RFP and used in the evaluation. Special care should be taken to review areas in which the specification is not detailed.

Often, after all the work of proposal evaluation is complete, the government may go into final negotiations with one or more contractors. Historically, since costs are often a major issue in those negotiations, MITRE has often been excluded from these final negotiations.

[36] *Source Selection Reference Manual*, M90-95, The MITRE Corporation, Bedford, MA, December 1990.

Government negotiators are not trained in the technical disciplines involved in the systems. Because of that, agreements may be negotiated in ways that negatively affect the technical performance of the proposed system. MITRE staff should play a role in the final negotiations. Experience has shown that participation by skilled technical personnel can avoid compromises in required operational capability, and in some other cases has actually saved the government considerable sums of money. If one works at it, MITRE can support the negotiation process without having access to the actual contractor cost proposals.

MITRE staff should play a role in the final negotiations. Experience shows that participation by skilled technical personnel can avoid compromises in required operational capability and can save the government considerable money.

There is only one important question to be answered here: Which contractor will do the best job—including performance, cost, and schedule—of providing a system that satisfies the requirements of the RFP and is most likely to provide the necessary system capability?

Monitoring Development Progress

This section reflects on the MITRE systems engineering activities that take place during the phase of the acquisition program in which the contractors are designing, developing, building, and testing the systems they have been contracted to provide. For the moment, assume that the government has contracted with a single industrial corporation that will provide the required system. MITRE's roles in preparing the system specification and in supporting the source selection process are technically challenging activities to the staff. The impact of their efforts on the program is direct and immediate. The importance of these efforts is readily appreciated by all program participants.

Although not as well understood and accepted, MITRE's work during the contractor development and acquisition phases is no less important to achieving the required system capability. Ideally, that work will have a positive effect on the success of the program, will be truly appreciated by both the government and the contractor, and will challenge the MITRE staff. However, those things will not happen unless the Corporation continues to focus on the capability that

is required as the criteria for action. It is especially important that MITRE work with both government and industry in cooperative and supportive ways. Some discussion of these points may help to clarify their meaning.

Chapter 3 discusses the desired relationship between MITRE and the government's system program director. Similarly, the characteristics of a positive association between MITRE and industry are outlined in that section. Many aspects of the interactions between MITRE and industry during the program development phase are discussed. For the purposes of the discussion here, it is assumed that the attitudes and approaches described there are operative on the program. Special emphasis here is on how the MITRE staff must view its effort in this phase for the work to be effective and satisfying.

During the contractor development phase, the Corporation has the responsibility to evaluate the adequacy and reasonableness of the contractor's analysis, design, implementation, and test activities. A major role of the MITRE project leader is to formulate and control the Corporation's work in ways that minimize the confrontational nature of the MITRE and industry relationship, and eliminate unnecessary effort while making positive contributions to program progress. In reviewing the contractor's technical progress, MITRE staff must identify critical technical progress and issues. The Corporation must work with the SPO to ensure that the industry provides the government with the necessary in-progress information, and—when required by the government—that the industry makes the changes necessary to achieve the system capability. At the same time, MITRE must avoid nit-picking in unimportant areas and refrain from creating unnecessary industry effort and costs. To do so, the staff must be technically accomplished in what it takes to carry out the critical system functions in the real world, vigilant in assessing the progress of the system acquisition, and effective in helping the SPO make any necessary changes in the contractor work or in the effort of other program participants.

Clearly, one major work area involves the review of contractor documentation and testing. To be successful at it, MITRE must

understand the capability the government requires and evaluate the contractor product in view of the contribution it is supposed to make toward achieving that capability. The contractor has legal obligations to the government for delivery of products. MITRE helps the government decide whether they have been satisfied, but that is not the most important reason for the MITRE review of contractor products. The Corporation is in business to help the government achieve a required capability. First and foremost, MITRE reviews contractor products to help achieve the capability, and only as a secondary concern to ensure contract compliance. There are subtle but vital differences in attitude and approach if the MITRE staff keeps that distinction in mind. These differences can significantly increase the Corporation's effectiveness in this phase of a program. Presumably, all organizations are working to achieve the capability. Some specific approaches that may be used by MITRE in interacting with industry during system development and testing are described in Chapter 3. They emphasize a cooperative effort among government, industry, and MITRE for the achievement of the required capability.

MITRE reviews contractor products to help achieve the capability, and only as a secondary concern to ensure contract compliance.

Naturally, this evaluation phase of the program becomes more complicated if there is more than one corporation under contract to the government to provide a portion of the required capability. All the discussion above, and in the sections referenced, still applies. But now there is an additional consideration of the interaction between the efforts of the various contractors. Again, MITRE will face situations in which difficult judgments must be made. Is the best course of action to force a contractor to comply with the contract requirements? Should the requirements be changed? Should one contractor's product be modified to accommodate something that has occurred in another's? The overriding criterion remains the same. What is the best thing to do at this time to achieve the required capability, all things considered? Are there MITRE efforts that would help the contractor? Those considerations include not just technical matters, but political, economic, and legal ones as well. These matters may become extremely complex. They are a challenge to the knowledge,

ingenuity, and statesmanship of the MITRE staff. When viewed in this light and approached in this way, the challenge of reviewing the contractor's progress is far removed from the mundane, contentious drudgery that it can become unless MITRE and industry have a cooperative approach in which each respects the capabilities and intentions of the other.

Other activities during the contractor design and development phase vary with the individual program. In an evolutionary development program, MITRE may be doing the studies and analyses leading to preparation of the system specification for the next program increment. The Corporation may be providing the systems engineering support required to initiate another program that will add to the system capability. All the factors that potentially dictate change continue to operate in the environment. The threat evolves, technology developments proceed, decisions are made that affect funding. Progress is made or delayed in other systems with which the current one must interoperate. The challenge to MITRE continues: to know in detail what is happening throughout the environment in which the system is being developed; to relate that to the specifics of the current program and especially to the contractor's work; and to work with the government program director to make whatever change is necessary to achieve the required capability on a reasonable schedule and at a reasonable cost. When performed with this perspective, review of contractor products has both great challenge and high impact.

Reviewing contractor progress is challenging and rewarding when MITRE and industry have a cooperative relationship in which each respects the capabilities and intentions of the other.

Much of this book has concentrated on system performance and to a lesser degree, on the cost implications of the many activities that take place during the acquisition of a major C^3I system. However, as has been noted repeatedly, a reasonable schedule is also a critical concern. In fact, in many instances the success and the cost of a program are driven in significant degree by the schedule. An overly ambitious schedule can be just as disastrous as miscalculations with respect to performance or cost. Also, when a particular activity is delayed, its revised schedule impacts not just that work, but potentially many other efforts as well. Quite frequently, in mapping out a

remedial approach to a problem, the schedule will become longer than originally planned. In that case, one has to decide whether to announce the new schedule or not. It is sometimes argued that if a new schedule is announced, people and organizations will not work as hard and as well as they might if the commitment to the original schedule was maintained. The argument suggests that any chance of improving on the new estimate will be lost by announcing it, or that announcing a new schedule for one activity may cause other work to be pursued less vigorously on the assumption that it too will have more time. There is some validity in these arguments, but there is also another side to the question.

Assume that the user command is to provide trained operational and maintenance personnel to participate in operational evaluation of the new system at a certain date. Personnel are to be reassigned from other activities, trained, and deployed to the test location. If a system development problem occurs that is likely to delay the start of system testing, failure to inform the using command of that likelihood could lead to a situation in which user command personnel would be relocated and find themselves without anything useful to do for many months. That is wasteful and obviously counterproductive to a cooperative attitude between the participants and therefore not in the best interest of achieving the capabilities.

As in most other perplexing matters of system acquisition, there is no universal answer on when to formally change a schedule. MITRE should strive to help establish the facts with respect to the prospective schedule, communicate the Corporation's assessments, and assist the SPO in applying the results to the current situation. MITRE must help the SPO evaluate the pros and the cons in each situation. The revised work must be explicitly defined, and realistic schedule and cost estimates developed and negotiated. A continuing series of "get well" activities disillusions everyone. Having established a realistic schedule, one must then decide when or if to announce it, and to whom. MITRE should provide advice that considers all related factors, not just those of a technical nature. Care must be taken by

the government in announcing and implementing change to avoid negating the existing contract with industry. Industry must be party to changes that affect the performance, schedule, or cost aspects of its contract. Otherwise, the existing contract may be voided and require complete renegotiation. Needless to say, MITRE must be sensitive to considerations of this sort.

Another important activity for MITRE in this phase of a program involves helping the SPO respond to all the requests for information and status reporting that always accompany an important acquisition program. Regular status reporting is required. Agencies both within and outside the DOD request information and either give guidance, make comments, or raise other questions. Many of these interactions serve legitimate management purposes; others are worthwhile investments in public relations. Whatever the objectives, each is important. The information must be factual and well presented. MITRE provides significant support to the program director in gathering the necessary information, assessing it, and presenting it to those that have legitimate access to it. The effort may require extensive technical work by the Corporation. It may also be very rewarding when the MITRE products are used to influence the course of the program in a positive way.

While the AWACS program was in the contract development phase, MITRE staff members were instrumental in analyzing the radar and communications performance, as well as the survivability of the AWACS platform. This analysis helped convince a high level review committee that acquisition of the system should be continued. Challenging, high visibility MITRE efforts of this sort arise on almost every C^3I acquisition program. They can occur at any point in the program. They are most often initiated because someone or some group is uneasy about an aspect of the program. Helping the program director to overcome any such bias, and in the process to create program supporters, are important MITRE activities. The visibility it affords is an opportunity for both the Corporation and the individuals involved.

To summarize the key questions to be addressed during this phase of the acquisition program, consider the following: Are the industry and government activities proceeding satisfactorily toward the achievement of the required capability? If not, what needs to be changed, and how? Similarly, are there events taking place in the environment surrounding the acquisition program that would dictate changes within the program? What changes, and how should they be accomplished? Are there any activities that have been overlooked but should be initiated? Are there any unusual opportunities that should be exploited to improve the program? Answering such questions characterizes the challenge to MITRE during this program phase much more appropriately than the somewhat cynical phrase "contractor monitoring."

Operational Testing

There is a large amount of testing that goes on as part of the contractor development efforts. MITRE is an active participant in those tests, helping to establish the test requirements and reviewing the contractor-proposed test program, test methods, data reduction, and analysis plans. The Corporation also is involved in establishing the levels of performance required, witnessing tests, analyzing data as appropriate, reviewing contractor test reports, and evaluating the results. When one considers all the subsystem and system testing of hardware and software, this represents a major activity for the MITRE staff. Beyond this level of testing, there are at least two others. The first is a series of system-level tests to determine whether the product provided by the contractor meets the requirements of the system specification as they are reflected in the contractor's top-level design and test documentation. The second level follows that and is aimed at determining whether the capability that has been acquired satisfies the operational requirements of the using command. It is not the purpose here to try to describe all of this in detail, but rather to make a few important observations about the latter two levels of system testing.

When the government signs a contract with industry to build a C^3I system, the industry is saying it will provide a system that meets the government's requirements as specified in the MITRE-prepared system specification. The government is saying that if the system is built as the industry proposes, it will be satisfactory. The top-level industry specification is reviewed by the government. When the government approves that specification, it is agreeing that if the industry builds a system that meets the industry specification, it will in turn meet the requirements of the MITRE-prepared system specification and therefore will satisfy the user requirements. The first system-level testing is directed at evaluating whether the delivered system meets the commitments made by industry in their top-level system design documentation. If so, the industry system is accepted by the government. There then follows a series of government-conducted tests to evaluate how well the system performs its operational mission. It should be noted that changes to the government's approach in areas such as when the contractor specification is approved are now under consideration.

As noted, MITRE is extensively involved in the various functional tests conducted as part of the contractor development program. Most of the initiative there is on the contractor's part. The contractor writes the test plans and procedures, conducts the tests, collects and analyzes most of the data, writes the reports, and submits them to the government. MITRE reviews the contractor plans, witnesses most of the tests, and evaluates the results. However, for system-level tests, some of the contractor initiative moves to MITRE. Early in the program, the Corporation prepares a test and evaluation master plan. The plan outlines all the testing that will be done on the system. For system-level testing, it attempts to anticipate any special test equipment, data reduction and analysis computer programs, personnel, and facilities that may be required to conduct the test programs. It establishes the performance measures that should be made and relates them to the requirements in the system specification. For each test measure, a level of acceptable performance is established. All of this

sort of information must be coordinated with both the development and operational communities.

For Air Force C^3I programs, a second set of system level tests is conducted by the Air Force Operational Test and Evaluation Command, an independent test agency. The tests are designed to evaluate how well the system performs the operational functions for which it was acquired. MITRE is actively involved in helping the test agency to understand what the system was designed to do, how its operational performance might be measured, and what test support will be required to carry out the test program. The Corporation is then very active in witnessing the tests and evaluating the results. The test agency makes its own independent evaluation. MITRE helps the SPO review that evaluation.

One of the most challenging aspects of the system test time is to distinguish those things that do not work as planned from those that work as planned but that someone now wishes to operate differently.

The firsthand experience gained by MITRE personnel in the development and evaluation testing is very important. It provides a firm, real-world basis for any work that the Corporation does on the current program. It is also a good learning experience that can be applied to the next program. Clearly, for programs developed in an evolutionary manner, knowing what exists is important in deciding what should be done next. But even when a system is not evolving, understanding what it does and how can be extremely useful for work on other systems with which it interfaces.

System testing is the culmination of the development cycle. By the time it takes place, much has happened that potentially changes agreements made at the beginning of the program. One of the most challenging aspects of the system test time is to distinguish those things that do not work as planned from those that work as planned but that someone now wishes to operate differently. Because MITRE provides a large fraction of the corporate memory on any long program, the Corporation must help the program director to distinguish these two problems. Both may occur, but unapproved changes in requirements should not be the basis for evaluating how well the development community did its job. This MITRE role requires experience, knowledge, and diplomacy.

As has already been stated, there are two key questions at this stage of a program: Does the contractor-delivered product meet the requirements of the system specification? Does the system perform well enough to satisfy the intended operational mission? In the end, nothing else matters. The answers to the above questions may, of course, spawn many other questions. The MITRE role as systems engineer requires that the Corporation be both willing and able to answer them.

Field Deployment and Operation

MITRE has always prided itself on going where the action is. Even in the very early days of the Corporation, MITRE personnel were in residence at places such as the Operational Air Defense Direction Center in Montgomery, Alabama. Over the years, MITRE people have followed other systems into the field, as well. Large numbers of MITRE staff have been resident at operating locations such as NORAD and Strategic Air Command headquarters. When special operational tests are conducted, MITRE staff members often attend. Activities of the kinds just mentioned have two major payoffs. The immediate one is that MITRE's background and experience in the systems being used can be applied to helping the users understand the system and to make maximum use of its inherent capabilities. On the other side of the coin, MITRE learns a lot about the command's operational mission and the limitations of their existing systems in supporting those missions. That information can be carried back to the development community and reflected in the Corporation's subsequent work for ESC in systems engineering of future C^3I capabilities.

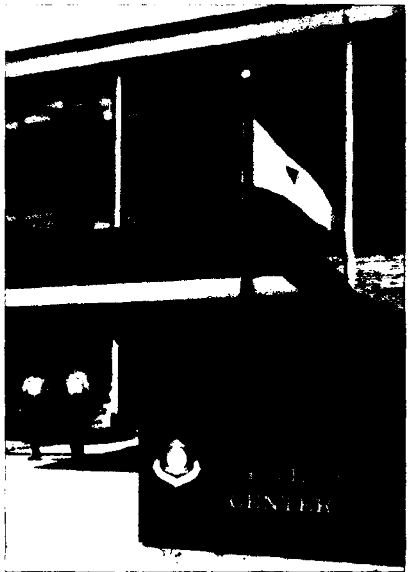
MITRE was formed at the request of the Air Force to provide systems engineering on C^3I acquisition programs. On occasion, there has been some uneasiness within the development community about MITRE's presence at operating locations. That uneasiness has stemmed in part from a concern that there have always been government-imposed and natural limitations on the size of the MITRE staff. Commitment of that staff to assist user commands in exploiting their existing systems reduces the staff available for systems engineering of

new C^3I capabilities. The Corporation has always been sensitive to those concerns; however, MITRE strongly believes it is essential for a limited number of its staff to work directly with the using commands. Those staff members can help facilitate the transition of new systems to the user, an important job of the development community. In return, the knowledge of the operational capabilities gained by MITRE can be applied to the next systems engineering job for the development community. As noted many times in this book, MITRE's understanding of the Air Force operational mission capabilities is both unique within the development community and essential to the Corporation's success in the systems engineering role.

MITRE strongly believes it is essential for a limited number of its staff to work directly with the using commands.


MITRE Staff at NORAD Headquarters

There is one other reason to encourage MITRE staff to participate in field deployments, field exercises, and field operations: it is a good reminder of why MITRE exists—to help the government achieve required capabilities. It is an experience of unparalleled dimension to see what one has worked so hard to accomplish operating as intended. This experience provides the satisfaction and encouragement required to keep the Corporation dedicated to helping in any way possible to provide the U.S. with the C^3I capabilities so vital to the nation's well-being.



ESC Headquarters, Bedford, Massachusetts

Relationship with Other Program Participants—the Environment

MITRE neither manages C³I systems acquisition programs nor builds the systems that result from these programs. Those functions are the province of the government's SPO and profit-making industry, respectively. As systems engineer on such programs, MITRE works closely with both the SPO (as part of the Integrated Product Team) and industry. The effectiveness of the Corporation's relationship with these key program participants largely determines the extent to which it can contribute to the achievement of required national capabilities. Significant efforts have been made over time to ensure that the normal role of MITRE as systems engineer on a government acquisition program is both appropriate and well understood. However, MITRE's role on any given program, and the extent of the contribution that the Corporation is able to make on that program, are a direct function of the relationships with the responsible program director and the associated industry. This section discusses a variety of factors that may influence these relationships.

Each of the major groups involved in a C³I system acquisition program—government, industry, and MITRE when it has the systems engineering role—exists and functions in a very complicated, dynamic

environment that from day to day may have profound impact on the conduct and success of the program. Understanding that environment and helping to deal with it as necessary, are major functions of the systems engineer. The final portions of this chapter summarize dimensions of that environment and MITRE's approach to it.

MITRE's Role in Support of the System Program Director, Director of Engineering, and the Integrated Product Team

The relationship among the system program director, director of engineering, and MITRE project leader is a critical factor in establishing the extent to which the Corporation can contribute to the success of a major acquisition program. The relationship of MITRE staff to other members of the integrated product team is similarly important. Although some of the material in this section describes the role of the MITRE project leader, it is important for staff to understand the attitudes and responsibilities that pervade the government/MITRE relationships when the Corporation assumes the systems engineering role. For MITRE to be successful, all of the staff must act in consonance with the Corporation's standards and methods.

There is no item in the federal budget that is labeled "MITRE." The Corporation's activity on a program must be justified by the program director and paid for out of program funds. From year to year, MITRE enjoys no guarantee of future funding. Clearly then, the Corporation must satisfactorily accomplish the work required by each program director and director of engineering for whom it provides systems engineering support. This must be done in ways that make MITRE the best choice for systems engineering from both performance and cost perspectives. MITRE's work on a project is delineated in a Technical Objectives and Plans (TO&P) document; that document, along with the TO&Ps for the other projects, is incorporated into the MITRE contract with the sponsoring agency. The TO&P is signed by the government program director or project officer and by the MITRE project leader.

With the exception of managing its own staff and other resources, nothing on the program is under the Corporation's direct control.

MITRE can neither legally direct the activities of government personnel, nor direct the activities of contractor personnel in any way that affects the scope of the contract that governs their work, the associated schedule, or costs. In fact, only the government contracting officer can give such direction. MITRE must work with the program director, director of engineering, and integrated product team to influence the events on a program. The Corporation is able to affect the success of a program through competence, initiative, persistence, and reputation. Most of all, MITRE is able to influence the course of a program by showing over time that its advice is correct, and that what the Corporation recommends is in the best interest of achieving the necessary system capability on a reasonable schedule and at reasonable cost.

As discussed in Chapter 4, an ESC regulation states that MITRE is expected to take the initiative in the interest of achieving the desired system capability. This means that the Corporation closely watches all factors that may affect the success of the program—not just the technical ones, but the political and economic, as well. When the Corporation recognizes that an action is required, it is incumbent on its project personnel to work with the program team to ensure that appropriate action is initiated and completed. MITRE does not have the role or the resources to fill in all the gaps. Some such activities may be appropriate for MITRE; most will have to be accomplished by other agencies and organizations associated with the program.

As stated in the introduction to this chapter, the environment within which C³I system acquisition programs take place is extensive and complicated. It is also very dynamic. Something unexpected arises every day on such programs. Important people ask questions and expect immediate answers, progress varies from what had been anticipated, a change in some detail must be made. The daily management challenge presented to a program director is almost overwhelming. Plans have to be canceled and new ones made. Long hours of work—nights and weekends, and extensive travel—are required.

A program director needs to learn who can be depended upon to be there when he or she needs help.

When MITRE assumes the systems engineering role, the Corporation is dedicated to doing whatever is necessary to achieve the needed capability, and that includes helping the program team in any way possible. Any ›tem problem that the program faces is a problem for MITRE. The Corporation's staff members are prepared to make the same sacrifices in time and travel that are required of the government personnel to achieve the capability. MITRE has repeatedly demonstrated a willingness and ability to go where the action is whenever necessary. On any given project, when the Corporation acts in this way, the program director and the other members of the program office believe the Corporation is a full partner, ready to do whatever is necessary to help them complete the acquisition program successfully. MITRE cannot assume the government's role, but can earn a working relationship in which the program director and the rest of the program team know that no matter what situation arises, the Corporation will find a way to help. MITRE becomes a full partner with the program office in carrying out the acquisition program. In such a role, MITRE staff may have a truly significant impact on achieving the required capability.

MITRE cannot assume the government's role, but can earn a working relationship in which the program director and the rest of the program team know that no matter what situation arises, MITRE will find a way to help.

While striving to be a full partner with the program office, MITRE must act as a professional organization. MITRE was formed as an independent entity in part because the government recognized a need for advice that was independent of the government itself. The government wants MITRE's best advice, and the Corporation is dedicated to providing it. Occasionally, there are times when some people in government do not want to hear what MITRE has to say. People tend not to want to hear that a program is heading for trouble, or that they should take out some risk insurance in a certain technical area, or that more money or time is needed, or that action must be taken to modify the existing program to achieve the capability. However, MITRE is paid to tell people what they need to hear, not just what they want to hear. Of course, MITRE has to act professionally in this

regard, recognizing the roles and responsibilities of the other program participants and especially those of the program director for whom it works.

As noted above, MITRE has to be available whenever needed. At the same time, the Corporation cannot provide "body-shopping" of technical staff to the government. MITRE is contractually committed to producing the products described in the TO&Ps, but the Corporation also responds to unanticipated program needs as they develop. Resolution of any conflict that arises is worked out between counterparts, or—barring resolution—ultimately between the system program director, director of engineering, and MITRE project leader. The MITRE project leader has two main functions. More than anyone else, the project leader, as the program director's MITRE focal point, has to be there when needed and must be fully cognizant of all matters related to the acquisition program. The project leader must act in such a way that the program director believes the Corporation will help in any way possible. As a second challenge, the project leader must ensure that the staff delivers products as required by the TO&P, while at the same time responding quickly to unanticipated program needs. The combination of these two demands is a significant management challenge for the MITRE project leader.

In each annual TO&P, the program director and MITRE project leader agree to a series of products that will be produced by MITRE over the course of the coming year. These products are explicitly identified and scheduled. The Corporation is contractually bound to meet those commitments, and the project leader is responsible for providing the products as required. At the same time, the project leader must adjust the use of the MITRE resources almost daily to respond to the needs of the program director. Some program directors and project leaders choose to write TO&Ps in ways that explicitly describe and limit the Corporation's commitments. Others feel it best to write the TO&Ps in more general terms to be free to respond to unforeseen demands. Whatever approach is taken, several things must be kept in mind: MITRE does not provide personal services; it

provides discrete products. The products to be delivered must be included in the TO&P, and the Corporation is legally responsible for providing them. The government is required to ensure that the products are delivered and are satisfactory. If during the year the program director and the project leader agree that the planned product deliveries must be changed in some way, then the TO&P must be modified. People sometimes complain that changing the TO&P is too time-consuming or not worth the bother. But it must be done. While the process is going on, any direction given to the Corporation that changes the planned products should be recorded in writing by the MITRE project leader and copies made available to the program director. It is important that the project leader keep the record of the MITRE commitments current and accurate. Changes in the work program should be made as necessary; the need to keep the documentation up to date should not inhibit such changes.

MITRE does not provide personal services; it provides discrete products. The products to be delivered must be included in the TO&P, and the Corporation is legally responsible for providing them.

In the ideal project leader/program director relationship, the program director asks the project leader's advice on all important matters related to the system acquisition before taking action. The project leader responds with timely, cogent advice that the program director can implement. To do so requires MITRE to perform the technical work necessary to provide a solid foundation for any recommendations. MITRE's advice is considered seriously and in most cases followed. When it is not followed, the reasons are discussed and agreed on. Over time, deep mutual respect develops and the program director believes he or she can count on the Corporation to help the program, no matter what the situation. Clearly, such a relationship is earned, not bestowed upon MITRE. On each project, the MITRE project leader is charged with earning such a role. When it is earned, the Corporation can have a major, positive effect on the success of the acquisition program and on the achievement of the desired capability.

Obviously, advice that the program director cannot implement does not help to achieve the capability. Worse than that, it indicates to the program director and to others that MITRE project personnel are not appropriately knowledgeable of important aspects of the

situation. Such occasions may also become confrontational when the program director does not try to implement the advice. At a minimum, giving advice that cannot be implemented undermines MITRE's relationship with the rest of the team; it tends to make the program director uneasy about the MITRE recommendations and may cause the program director to double-check everything the Corporation says. A relationship in which the program director feels it necessary to independently verify everything he or she hears from MITRE is unsatisfactory, both for the government and for the Corporation. For the government, it is costly and counterproductive. For MITRE, the project staff will resent having their advice constantly subjected to a second opinion. Carried to an extreme, such a relationship is counterproductive to the achievement of the capability. MITRE does not expect its advice to be blindly accepted and implemented. However, MITRE seeks a relationship in which it is able to provide responsive, insightful advice that is valuable enough to become the preferred program office course of action. This professional respect must be earned. In part, it is earned by demonstrating that the Corporation understands all the circumstances surrounding the situation at hand, and factors them into providing implementable advice.

MITRE seeks a relationship in which it is able to provide responsive, insightful advice that is of sufficiently high value that it becomes the preferred program office course of action. This professional respect must be earned.

As obvious as the need for implementable advice may seem, it is important to stress here, since the circumstances that surround program decisions are often very complicated. Rarely, for example, is the resolution of a problem, or the seizing of an opportunity, limited to strictly technical considerations. In addition, the decisions that must be made during a major acquisition program have significant factors that are judgmental in nature and not amenable to strict measurement. In making such decisions, one is often attempting to predict things that may not occur for many months, or even years. It is therefore very difficult to achieve a relationship in which the program director has implicit faith in the applicability of MITRE's advice. Unfortunately, even one case in which the Corporation's advice is inappropriate for the situation can badly damage the MITRE/program director relationship. To earn the role of privy counselor, MITRE

must fully understand all the circumstances under which the program director is operating and make its recommendations accordingly. Compromise among the salient factors is often necessary.

As MITRE demonstrates a record for good advice, there is less need for the Corporation to prove what is being said beyond a shadow of a doubt before the program director will take action. As in everything, to do something different from what one is currently doing takes time, effort, and often resources, such as money. If MITRE suspects a problem, it is only natural that a program director will want to be sure of the situation before taking action, such as redirecting a contractor. On the other hand, the longer one takes to react to a suspected problem, the more difficult and costly it will be to rectify. The Corporation must avoid crying wolf every time a problem comes up. At the same time, it must work to identify important problems—or opportunities, for that matter—as early as possible and to take action on them as soon as the evidence suggests that a change is in order. There is every reason for a program director to want to delay dealing with a potential problem until the contractor in question owns up to it, especially if the contracting situation is such that the problem clearly lies with the contractor. If the government brings up the problem and directs a change, the cost of the change may fall to the government. If the contractor admits to the problem first, that contractor may be liable for the associated costs of the change. This is a very important consideration, and MITRE must weigh it heavily. However, the overriding consideration should always be the best thing to do under the current circumstances to achieve the required capability in a timely and cost-effective manner. Sometimes, MITRE must firmly and professionally urge the program director to take action in the name of the capability, even when the action will cost the government money and resources to take the initiative.

Some of the factors that one may consider in assessing the strength of MITRE's relationship with the program director on any given project are listed below:

- Is the MITRE staff fully informed of all program-related matters as soon as they occur? If the Corporation has only

selective access to information, or if the staff hears about events only long after they take place, the relationship is not good, and MITRE's ability to help as systems engineer is correspondingly diminished.

- Does MITRE get a chance to advise on all important program matters? Again, if not, the Corporation cannot perform as well as it might in the systems engineering role.
- Does MITRE have to prove everything it says beyond a shadow of a doubt? Is the Corporation's advice accepted as professional advice? If the first response to any MITRE advice is skepticism, the relationship is poor and the Corporation's impact will be low and unnecessarily costly.
- Are MITRE people participants in all key program meetings, especially those with higher headquarters personnel and with user representatives? It is critical for MITRE people to hear firsthand what other program participants believe.
- Do MITRE people get a chance to discuss those subjects that the Corporation understands best when they are presented to agencies other than the program office? If MITRE knows the material best, its people can do the best job of discussing the material with others. This approach also gives other agencies an appreciation for the Corporation's contribution to the program, a question often on the minds of people in Washington who have to pay the bills.

MITRE cannot substitute for the government in a program direction role and must avoid appearing to do so while still filling the legitimate role of the systems engineer.

None of the above has to be done in a way that makes it appear that MITRE is appropriating the role of the system program director. If it appears that MITRE has usurped the responsibility of the program director, whether true or not, the program may be hurt. MITRE cannot substitute for the government in a program direction role and must avoid appearing to do so while still filling the legitimate role of the systems engineer. If the project leader and program director have

developed a sense of mutual trust and respect, their joint efforts will be perceived as cooperative and healthy. Their achievements will far exceed those of any relationship in which MITRE merely proposes actions, the program director disposes as he or she sees fit, and the Corporation is content with the result, regardless of whether the advice was followed. MITRE needs to understand and accept situations where its advice cannot be followed, or when it is judged inappropriate at the time rendered. However, when the Corporation is giving good advice, such occasions should be rare.

Although MITRE cannot assume the role of the government in program direction, its personnel may be asked to chair meetings, witness tests, and do other tasks that might normally be done by government personnel. However, the results of such activities can be enforced only by government personnel. Occasionally, MITRE is asked to take on extraordinary roles when government personnel are unavailable. Each occasion is carefully negotiated to be sure that the Corporation's role is in strict compliance with government regulations. In two cases—the Strategic Air Command Digital Information Network (SACDIN) and Peace Sentinel programs—MITRE was asked to assume the functions normally performed by the program office engineering divisions.

For SACDIN, the SPO did not have an engineering division and MITRE was asked to assume many of the functions normally carried out by such a division. The activities performed by MITRE and its experience in that role are described in detail in a MITRE paper.[37] The paper also describes MITRE's relationships to the various directorates within the SACDIN SPO.

Peace Sentinel was the ESC acquisition program that provided Saudi Arabia with its own AWACS aircraft. MITRE was asked as part of the system engineering role to assume the usual functions of the SPO engineering and test directorates. The Corporation was directly involved in contractor negotiations, a very important activity

[37] *MITRE/SACDIN System Engineering Role*, WP-28718, The MITRE Corporation, Bedford, MA, February 1990.

that sometimes seriously affects the success of a program and to which MITRE's technical knowledge and operational understanding can make important contributions. The Corporation initiated technical interchange meetings with other participants and often chaired them. Both technical and programmatic aspects of a subject were always considered. MITRE became more directly involved in coordination within the program between the SPO divisions and between the SPO and other agencies, such as Air Force Systems Command and the Air Staff. MITRE was responsible for helping to coordinate its technical contributions with the information from the other SPO divisions, such as program control, and to provide the implementing correspondence for signature by the system program director. MITRE helped the SPO prepare for program reviews and prepared and briefed program-wide position papers and action item status. This expanded role involved the Corporation in much of the great volume of correspondence that typifies a SPO activity, and it consumed valuable MITRE resources. This was compensated for by a much greater opportunity to contribute to a very successful program. All the Corporation's effort was conducted in an atmosphere of significant U.S. political concerns with an associated international dimension. MITRE's accomplishments on the Peace Sentinel Program were recorded in an unnumbered MITRE paper.[38]

To complete this discussion of MITRE's systems engineering role in support of a system program director, two matters of some sensitivity deserve to be mentioned. One concerns the situation in which a MITRE project leader and a program director have a difference of opinion on a matter judged to be important to the success of the program. In such a situation, the MITRE project leader is expected to discuss the matter with his or her supervisor, who may in turn discuss the matter with the program director. Higher levels of corporate management may also become involved. In cases where the situation is deemed by MITRE management to be of serious concern to the

[38] *Peace Sentinel Program, Program Achievement Award*, Vol. 1, The MITRE Corporation, Bedford, MA, 1987.

success of the program, and where satisfactory resolution cannot be achieved with the program director, MITRE management will discuss the situation with the program director's management, up to and including the Commander of ESC, in the case of the Air Force. The Corporation will support whatever decision comes out of that process. This process is sometimes the cause of friction between MITRE and Air Force program directors. Everything possible is done by the Corporation to keep the program director fully informed and involved in all such discussions. The discussions are intended only to ensure that when a serious matter of major program import arises, and when MITRE's advice is not followed, that the Corporation's contractual obligation to ESC is fully discharged.

A second area that is sometimes controversial is the interaction of MITRE people, especially senior management, with DOD and Air Force personnel involved in some way with an acquisition program. Such interactions can be of great concern to a program director unless they are handled very carefully. On the other hand, if the relationship between the program director and the Corporation is healthy, the ability of top corporate management to talk to senior officials in the DOD and the Air Force can be of great benefit to the program director and to the acquisition program itself. MITRE management's normal

Deputy Secretary of Defense William Perry at MITRE-Bedford

responsibilities bring them into regular contact with such officials. When a program director wants to deliver a message or gain some necessary information, MITRE management can be an effective means for doing so. Everyone—the program director and his or her supervisors, along with MITRE staff and management—needs to recognize the value of such a process when well done, and the potential for serious problems if it is not. The process can work well if MITRE people are careful not to abuse it. The more astute program directors recognize that this MITRE ability can be helpful in accomplishing tasks or obtaining information that they might find difficult to achieve without going through many time-consuming layers of review.

The challenge of the responsibility and the chance to do something significant toward the achievement of important national capabilities are the reasons that dedicated professionals work at MITRE.

When the desired MITRE role is achieved, the Corporation is in a position to have tremendous influence on the success of the program. That position places a formidable responsibility on MITRE to ensure that its advice is indeed in the best interest of achieving the required capability. This role and the associated responsibility are the challenge and the satisfaction enjoyed by the MITRE staff. They are the reasons that dedicated professionals work at MITRE—the challenge of the responsibility and the chance to do something significant toward the achievement of important national capabilities.

MITRE is prepared to take extraordinary steps to help the government achieve required capabilities and often does so on programs for which it has systems engineering responsibility. At the same time, both the Corporation and the government must observe the rules that govern the use of organizations such as MITRE. The Corporation cannot usurp the roles of either government or industry, cannot body-shop staff, and must studiously avoid even the appearance of a conflict of interest. Only in these ways will the special relationship between the Corporation and the government be preserved for future important acquisition programs.

MITRE's Relationship to Industry

MITRE is paid by the government to act on the government's behalf in achieving required system capabilities. However, neither MITRE nor the government builds the systems—profit-making

industry does. Without industry, there are no systems. A part of the Corporation's role, then, involves helping the government get what it needs from the industry that builds systems. In that role—when MITRE is working effectively—the Corporation can be as useful to industry as it is to the government.

Clearly, a confrontational relationship between the government and industry, and/or between MITRE and industry, is counterproductive to achieving the required capability. MITRE staff should strive for a relationship of mutual respect and understanding with industry. This is especially important among the key people in each organization. Each group should feel the other is dedicated to doing its part to achieve the required capability and is making contributions to providing it. Industry should feel that the Corporation exists to help them, not harass them. MITRE should feel that industry is doing everything reasonable to achieve the capability, not just the minimum they can get away with. Realizing such a relationship in the real world is not easy to do, but it is an important ingredient of a successful program. It is fostered by frequent, open discussion at all levels and by offering constructive suggestions, rather than just criticism. Mutual respect between the Corporation and industry grows or erodes, as the case may be, as the program passes through the various phases of acquisition.

Because of MITRE's role between industry and government, the Corporation is often placed in situations in which it evaluates the products of industry against the government's requirements, or in which it assesses the progress of industry in accomplishing its contractual commitments. MITRE staff must act as an honest broker and must constantly ask, "What is the best thing to do, under the circumstances that prevail at this time, to ensure the required capability is achieved in a reasonable time and at a reasonable cost?" Often, the answer to that question will require both government and industry action and may meet resistance on both sides. In this process, one needs to separate carefully what is best to do at this time from how the circumstances developed and who should reimburse whom in

view of the required changes. Forcing contract compliance may not be the best action. The existing contract is an important factor, but not the only one. Once agreement is reached on what needs to be done, fault and liability can be adjudicated. Resolution cannot be achieved the other way around, although many will wish to talk more about liability than capability.

MITRE's relationship with a particular contractor on a given program is in part established by what has taken place on earlier programs in which the two have worked with one another. However, the relationship results mainly from the interactions that take place on the current program. There are always many opportunities for MITRE to make positive contributions to industry efforts.

Forcing contract compliance may not be the best action. The existing contract is an important factor, but not the only one.

The process used by the government to select a contractor to build a system involves competition among industrial companies able to do the job. This process is known as source selection. The competition is based on who can do the job, and for what price, as represented by industry proposals. This approach forces a contractor to propose as much capability as possible, for as low a price as possible, to win the competition. Whether some alternative approach would result in better systems is not a subject of this book. During source selection, MITRE helps the government narrow down the proposals to those that are most responsive to the government's requirements, and then to choose the best from that list. The Corporation does not have a vote on which company should be selected but provides technical evaluations of contractor proposals to those government people who do. A contract should not be awarded when the government believes that the program cannot be accomplished for the time and money proposed. This is a critical concern. Both industry and government must believe that the job can be done within the available time and money. MITRE must be prepared to attest to that belief at the time of contract award, or to recommend alternative courses of action to provide consistency among the required capabilities, money, and time provided in the government/industry contracts. A program that is initiated on any other basis is certain to have major problems during acquisition.

MITRE's capabilities are clearly useful in assessing the technical quality and feasibility of industry proposals submitted in response to a government RFP to build a new system. With strong professional people from MITRE involved, corporations may expect that the technical strength of their proposals will be recognized and will be a major factor in the award of the contract. MITRE's knowledge of what it takes to build certain capabilities helps the government to estimate the realism of contractors' price and schedule proposals and to differentiate fairly among the proposers.

With a proper foundation, all participants can assume a good-faith attitude as the program begins. In particular, the contractor will begin the program with the approach that it fully intends to deliver what is required by the contract, within the time and resources provided. MITRE's attitude about the contractor must reflect the belief that the contractor is so committed. The Corporation is not in the business of trying to manipulate the situation to extract the last ounce of capability from the contractor, whether the contract provides for it or not. MITRE is not driven by the belief that contractors are out to exploit the government for corporate gain. At the same time, MITRE staff cannot be so naive as to believe that no matter what happens, the contractor will deliver as required by the terms of the contract.

As the program proceeds, MITRE's technical skills, experience with related mission capabilities, and understanding of the government's requirements can be helpful to the industry in meeting its contractual commitments.

As the program proceeds, MITRE's technical skills, experience with related mission capabilities, and understanding of the government's requirements can be helpful to the industry in meeting its contractual commitments. MITRE can help industry translate government requirements into industry technical specifications to be used as the basis for constructing the system. Interpretations can be provided and questions answered. One MITRE activity that has proved successful is working directly with the contractor early in the program, sometimes at the contractor's plant, to clarify any questionable areas in the government's specification. In that way, the contractor work will get started in the right direction and the need for later redirection will be minimized. Mutual respect and confidence will be built. Such dialog should continue throughout the program. As discussed below, both MITRE

and the contractor must recognize that MITRE cannot legally direct the contractor in any way that affects the performance, schedule, or cost aspects of the government/industry contract. Despite that, the Corporation's advice and counsel can be helpful to the contractor in meeting the terms of its contract.

Conflicts may arise in trying to help both government and industry achieve the required capability. These conflicts may involve questions of whether the contractor has done what was promised, or whether the government has changed its requirements, or even whether the job is still doable or desirable. Helping to resolve those conflicts in the best interests of attaining the required mission capability is a major challenge to MITRE staff. The Corporation's technical capability and familiarity with the details of the contractor's work can be of great value to industry, as well as to the government, in such situations. MITRE's capability on the government side provides a realistic appreciation for the contractor's technical situation. The government is not in a position where its only option is to insist that the terms of the contract be met. Alternative actions can be evaluated from operational, technical, and contractual points of view. Because the detailed specifics of the situation are better understood on the government side, the treatment of industry can be more equitable than it would be otherwise, and the bitter discussions that sometimes accompany adjudication of fault for program failures can be minimized.

When MITRE observes that the contractor is not fulfilling the requirements of the contract, or that the contractor design has flaws, or that the tests have failed, the Corporation has a responsibility to say so, clearly, openly, and professionally.

It is also clear that MITRE's technical knowledge can raise difficult questions for industry. However, in the long run, achievement of the required capability will depend on good quality technical work by the contractor. The sooner a problem area is identified and any necessary changes implemented, the more likely the contractor will provide the required capability, an objective in which the contractor shares. When MITRE observes that the contractor is not fulfilling the requirements of the contract, or that the contractor's design has flaws, or that the tests have failed, or whatever, the Corporation has a responsibility to say so, clearly, openly, and professionally. Suggestions for fixing the problem should also be offered. In some sense, then, MITRE represents

a threat to the contractor, a government capability that can cause trouble for the contractor, trouble that might not arise if the Corporation were not working on the program.

Thorough review of contractor efforts is one of the major thrusts of systems engineering. MITRE should direct itself to those issues that really make a difference in whether the capability is achieved. Harassing the contractor on every little point is counterproductive to achieving the capability, since it provides no improvements, creates animosity, and wastes resources all around. If the Corporation has earned the respect of the contractor, acts professionally, and restricts its considerations to those that in some significant way affect achieving the capability, it will be able to critique the contractor effort and have a positive impact. MITRE is not in the business of criticizing contractors. Quite to the contrary, MITRE is in the business of helping contractors build the required systems.

When MITRE and contractor personnel have a difference of opinion on a technical matter, the Corporation's staff must be careful to include all relevant factors in coming to a recommended action, not just those of a strictly technical nature. MITRE technical people must include in their assessment the real-world practicality of the contractor taking MITRE's approach, fully considering the contractor's obligations, what has transpired on the program to this point, and the best interests of achieving the required capability. MITRE must avoid the "ivory tower" approach that industry sometimes feels characterizes its recommendations. MITRE's staff must be very knowledgeable about all factors, and equally pragmatic. Over 60 percent of MITRE staff is hired directly from industry, and an even larger percentage has had industrial experience. That experience should be reflected in the Corporation's recommendations.

In every acquisition program, the contractor is required to provide a significant amount of documentation for government review and approval—specifications, test plans, test procedures, etc. Preparation and review of this documentation is a very costly and tedious process that can be detrimental to progress if not handled carefully. An

approach in which industry prepares its documents without in-process interaction with the government and MITRE, hands the documents over to the government, and receives comments back, is a prescription for failure. The process will take several iterations before both sides can agree on an approved document; in the meantime, resources will be wasted on both sides and animosity will build. MITRE and the government must work closely with the industry as the documentation is produced. Industry should feel free to ask questions and should get timely, definitive answers. Comments and rewrites should be prepared more as a team, and less as a "we versus them" contest. MITRE staff should expect to spend time explaining their comments and making suggestions for improvements.

Contractor documentation is of interest only to the extent that it contributes to achieving capability. Each required document should be evaluated accordingly.

Contractor documentation is of interest only to the extent that it contributes to achieving capability. Each required document should have a purpose and should be evaluated accordingly. Purposes may include describing what the contractor plans to do for the government; describing what the contractor has done; or permitting someone other than the contractor to operate and maintain the system. Each document has to be adequate to serve its purpose—adequate, not of Pulitzer Prize quality, not ideal, not even excellent. To repeat an admonition made elsewhere in this book, the Corporation's comments should distinguish those that are truly important to achieving the capability from those that are merely to make the document neat. MITRE should work directly with the contractor in resolving the important ones and place significantly less emphasis on the remainder. Clearly, however, it is the contractor's responsibility to ensure that both the technical and editorial quality of its documentation are adequate to support successful system development and implementation.

Another facet of MITRE/industry relationships involves the study of potential program actions or changes. There will be many times when someone will propose an addition or deletion to the system being built, or will propose some change in the way the system is designed or built. These proposals will generate many "what if" studies, studies that for the most part will not have been anticipated

when the program began. MITRE must be very careful in recommending that industry undertake such studies. Industry may have to be involved, since it may well have the information necessary to make a meaningful assessment of the proposal, and since the results may affect the work program. Such studies obviously consume industry resources that were allocated to the existing program. But more than that, whether the studies are conducted by industry, MITRE, or some other group, they raise an uncertainty in all parties about how to proceed pending their outcome and the resulting government decisions. This uncertainty can be very costly as people delay, awaiting the outcome. Some such excursions are absolutely necessary and require industry participation. However, too much of this sort of thing undermines the resolution of the program participants and can result in large costs to the program and significant delays in achieving the required capability. A key part of the MITRE/industry relationship involves the proper participation of both groups in the study of alternative courses of action.

The inevitability of change on a major acquisition program is emphasized throughout this book. Many of these changes will impact on the contractor's activity. Some will require modification of the contract, and some will be caused by the contractor's actions or lack thereof, or by factors outside the contractor's control. As a group, MITRE project personnel must be well enough informed to recognize the necessity for change and the reasons for it. They must understand the potential impact on the resulting capability if change does not take place, or of alternative changes that might be made. In particular, with respect to industry, the Corporation must be able to differentiate those changes that should be handled within the existing contract from those that require contract modifications. As noted above, MITRE staff cannot naively assume that the contractor will do whatever is necessary to achieve the capability. Each of the major players—the government, industry and MITRE—has limited resources, is concerned about doing its part, and wants to maintain a good reputation. Industry does not have unlimited funds and is

properly and understandably not willing to assume responsibility for events outside its contractual provisions. MITRE simply cannot afford to assume that somehow the industry will take care of every problem that arises. The Corporation should make it clear when industry should do so; when additional resources are appropriate, it should counsel the government to provide them.

Another temptation faced by MITRE staff when a problem occurs is to pitch in and help write the contractor test plan, or help the contractor produce some other product for which it is responsible. The staff can get frustrated at telling the contractor what needs to be done and then not having it done. They may conclude it would be less effort to do it themselves. On very rare occasions, that is the right course of action. But there are two words of warning: First, the contractor is responsible for those products, and if MITRE usurps that responsibility, the Corporation is in some sense liable for the results. Even though the Corporation cannot legally direct the contractor, MITRE initiatives such as this are the basis for subsequent arguments about who is at fault when things go wrong. Second, the government cannot afford to pay both organizations to do the same job. With limited resources, MITRE would have to detract from another of its responsibilities on the program to assume one of industry's tasks. Therefore, such activity must be negotiated with the system program director and arranged with the contractor. Despite these concerns, on occasion, the best interests of achieving the capability dictate such initiatives. They should be undertaken only with the full understanding and support of the system program director.

Only the contracting officer can give the contractor direction that changes the contract's performance requirements, schedules, or costs.

Although not as prevalent today as it was years ago, there are often references to MITRE giving technical direction to the contractors on programs for which the Corporation has systems engineering responsibility. It should be noted that only the contracting officer can give the contractor direction that changes the contract's performance requirements, schedules, or costs. MITRE cannot give such direction; MITRE staff and contractor personnel need to understand that. The

contractor cannot use a MITRE statement as a basis for doing something different from what is required by the contract. MITRE staff cannot expect them to and should not attempt to influence the contractor in that way. On the other hand, the Corporation's activities can have great impact on what the contractor does. The government specification prepared by MITRE helps to direct the contractor's activities, as do conversations in which the Corporation provides interpretations of those specifications. The specification is contractually binding on the contractor, but its interpretations are not. MITRE comments on contractor documentation, contractor progress, or test results are all a form of direction when provided through the SPO, but become contractually directive only when the contracting officer makes them so. The Corporation can have significant impact on the technical direction of the contractor's activities, but only the contracting officer can give technical direction.

There are other significant ways in which MITRE interacts with industry outside individual programs. Key MITRE people meet their counterparts in industry to discuss common interests and corporate relationships. Both MITRE and industry people serve on various government committees and through these associations build mutual respect. The Corporation regularly exchanges information with its industrial counterparts concerning technology developments. In this way, the top technical people get to know and respect one another. MITRE may suggest new areas that are of interest for future government systems and represent new opportunities for industry. Such information is useful to industry in its determinations of where to invest resources in anticipation of future business. Industry may describe new technology that is becoming available for use by the government. The knowledge of new technology gained by the Corporation is helpful in assisting the government in establishing new acquisition programs designed to fill critical government requirements. Many of the MITRE/industry discussions include industry proprietary data. MITRE procedures require that proprietary data be protected as carefully as classified information.

This section has discussed MITRE's interactions with the major industrial corporations with whom the government has a contract for delivering a system. They are the prime contractors. However, there are a large number of subcontractors that provide portions of the system to the prime contractor, who in turn delivers the system to the government. The contributions of the subcontractors are critical to achievement of the capability, but subcontractors work for the prime contractors; they are not under contract to the government. Many major failures on acquisition programs have resulted from problems between prime and subcontractors. It is therefore very important that MITRE be cognizant of the prime/subcontractor relationships at the time of contract. The Corporation must monitor events in that area throughout the program. Important issues between the prime and the subcontractors that affect achieving the capability must be raised by the Corporation in a timely manner. This may not be easy to do. It will often be difficult to get the required information; the prime contractor may feel its dealings with subcontractors are its business and not the government's. However, MITRE must take the initiative in the name of achieving the capability, and the quality of the MITRE/industry relationship will determine how effective the Corporation can be. When the industry believes MITRE is both knowledgeable and acting in the best interest of industry, it will cooperate for the good of the program. Again, the relationship must be earned by MITRE. In any case, the history of acquisition programs is replete with examples of contractor/subcontractor problems. It is an important area of MITRE concern as systems engineer.

The history of acquisition programs is replete with examples of contractor/subcontractor problems. It is an important area of MITRE concern as systems engineer.

There is one other segment of industry with which MITRE may interact when assigned the systems engineering role on a C^3I system acquisition program. When the government requires assistance that is inappropriate for MITRE, or when the Corporation cannot provide the required resources, the government may hire another contractor to provide that assistance. This is not a new or unusual situation. When MITRE was unable to provide all the assistance required in the area of personnel subsystems on the SAGE system in the late 1950s, the

government hired a contractor to provide analysis and documentation support. MITRE worked with that contractor to ensure the applicability of their products. More recently, the number of C^3I systems that the government is attempting to acquire has increased more rapidly than the in-house government resources available to manage the programs. This has resulted in a significant growth in the number of tasks the government has had to contract with organizations other than MITRE or the companies building the systems. These contractors are known as System Engineering Technical Assistance (SETAs) or Technical Engineering Management Services (TEMS) corporations. In many cases, there is little overlap between the work of these companies and MITRE's work as systems engineer, but overlaps sometimes do occur. For example, a separate contractor may have responsibility for independent verification and validation (IV&V) of software supplied by the system contractor. MITRE too is concerned with the adequacy of that software. To help manage that overlap, the Corporation remains cognizant of the IV&V contractor's work and incorporates the results into the Corporation's recommendations to the SPO.

In summary, MITRE can achieve a cooperative and constructive relationship with industry without appearing to take over the industry's responsibilities and without abrogating its responsibilities to act in behalf of the government. Again, mutual respect and trust among key people in government, industry, and the Corporation are essential ingredients. A relationship of this sort must be earned by MITRE on every program for which the Corporation has systems engineering responsibility.

The Acquisition Environment

MITRE is responsible for achieving a thorough, realistic understanding and appreciation for the mission capabilities that the user commands are attempting to achieve. As a second major challenge, the Corporation must be fully aware of the total environment in which every system acquisition takes place. For military systems, that environment was characterized by A.D. Hall in 1962:

But let the management be the United States government trying to provide the military security of the nation, and let the functions of research, systems engineering, development, manufacture, and operation be dispersed among hundreds of organizations—then these objectives are approached only with the greatest of difficulty.[39]

A similar description of the government acquisition process was given by the former commander of the Air Force Systems Command, General A. Slay (U.S. Air Force retired) in his testimony to the Senate Appropriations Committee in 1981:

In the systems engineering role, MITRE must thoroughly understand the universe in which the system is being created and must be willing and able to adapt to that environment.

We now face a situation in which at least seven organizational layers or echelons do the same jobs...and, far from paying their way, these multiple layers significantly reduce the effectiveness with which the overall systems development and acquisition mission is performed.

Today, most important decisions on Air Force acquisition programs are made remote from the Program Office, usually by people who have never been a Program Manager, have never negotiated a contract, who have never used an Air Force weapon system in combat, and who have no technical or management expertise on the program in review.[40]

In his latest book on systems engineering, Hall defined a system and its environment as a "universe" or a "supersystem."[41] In the systems engineering role, MITRE must thoroughly understand the universe in which the system is being created and must be willing and able to adapt to that environment.

MITRE has no direct control over any portion of this environment. On the other hand, the more MITRE understands of the environment, the more likely its advice will be timely and effective. The

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[39] A.D. Hall, *A Methodology for Systems Engineering* (Princeton, New Jersey: D. Van Nostrand Company, Inc., 1962), p. 12.

[40] *Aviation Week and Space Technology*, August 18, 1981, p. 11.

[41] A.D. Hall, *Metasystems Methodology* (Elmsford, New York: Pergamon Press, 1989), p. 25.

more MITRE is able to help the program director accommodate that universe in conducting the acquisition program, the greater the probability that a timely, cost-effective mission capability will be achieved. It is also true that the program director has little direct control over many of the factors that affect his or her program. MITRE can be of real assistance to the program director by being aware of the environment surrounding the program and by providing timely advice on how to deal with it in a proactive manner.

Before describing some specific aspects of the environment one finds in most acquisition programs, a few general characteristics are worth mentioning. The environment is very large, complex, and extremely dynamic. One never knows from day to day who among all the players will ask an important question, make a declaration, or announce some finding or decision that impacts the program in an important way. Significant resources of all parties are consumed in responding to these situations. Many of them are not productive, but often they cannot be ignored. Some of them will occur repeatedly on a program. For example, the ability of a system to perform in a countermeasures environment is a debate that goes on throughout the program as the system evolves, the enemy threat increases, people invent new scenarios to challenge the system, special review groups examine the system, and new people assume positions that provide some relationship to the program. As a full partner with the program director, an important part of MITRE's systems engineering work is to be cognizant of this environment at all times and prepared to help deal with it in all its dimensions. Most especially, the Corporation must be prepared to handle the most difficult technical questions in any arena in which they come up.

The program director works in a complex system universe. First, there is always an existing mission capability on which the new one will be imposed. Therefore, the planned system will always be a mixture of new and existing elements. To be successful, the new capability must provide for evolution from the existing one. Similarly, the new capability will evolve over many years, and new features will

be added as they become available. Lack of resources, technology limitations, and the rate at which the user can absorb new capabilities may all require a phased implementation.

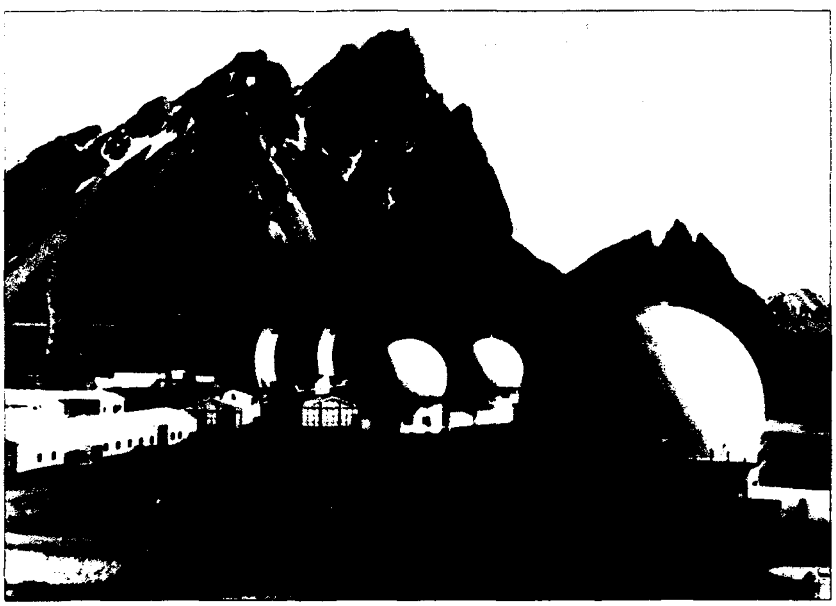
As described in Chapter 2, the current DOD acquisition process develops individual subsystems, or pieces of a mission capability. Each subsystem is bounded in function, time, and money. No provision is made in the individual programs for combining all the subsystems into a mission capability. That task is left as an exercise for the using command. MITRE has a capability orientation and is involved in the acquisition of many of the subsystems that constitute the capability. While helping the government in providing the separate subsystems that go to make up the mission capability, the Corporation has both a special knowledge and a special responsibility to help in achieving that capability. This approach helps the Corporation advise the program director on actions to ensure the subsystem being acquired integrates well with the other existing and planned pieces of the capability. This approach expands the universe extensively. It is also crucial to achieving effective mission systems.

MITRE has a unique opportunity and therefore responsibility to help accommodate interservice and international considerations in the acquisition program.

In programs where interoperation with other services is involved, or where operations with the forces of other nations are required, the considerations of how the new capability fits with existing ones are made immensely more difficult to understand and accommodate in the program. To be cognizant of these factors and see that they are factored into the current program is one of MITRE's major system engineering challenges. On the other hand, MITRE has worked on many different programs with all the U.S. military services, and on a large number of systems that the U.S. has helped to acquire for other friendly nations. As a result, the Corporation is uniquely knowledgeable about programs that involve interoperation among U.S. services or with U.S. allies. It is important to place the current system in its proper universe. Again, MITRE has a unique opportunity and therefore responsibility to help accommodate interservice and international considerations in the acquisition program.

To make matters in this regard even more challenging, the system that is being built will most likely have to interact with other systems currently in acquisition or planned for future acquisition. Again, these programs can have major impact on the system being acquired. The capabilities to be provided by these other programs must be appreciated by MITRE as systems engineer and their real and potential impact built into the acquisition program. This challenge is made more difficult by the tendency for the government to buy subsystems rather than capabilities, as described above. The interactions between the subsystems—the interfaces—tend to get inadequate attention. When one recognizes an interface problem, it is difficult to convince any program director to take the initiative to provide for the interface. Quite naturally, with bounded direction and often with very limited resources, a program director concentrates those resources on the system for which he or she has explicit direction.

On the other hand, MITRE's preoccupation with the overall capability available to the user demands that the Corporation recognize interface limitations and work to establish how the problems will be overcome and by whom. MITRE people cannot content themselves with being experts on the particular subsystem for which they have system engineering responsibility. They must also be experts on the



Iceland Air Defense System Site #3

other subsystems that contribute to the overall mission capability. MITRE has had system engineering responsibility for many of these systems, and with that responsibility comes a bigger one—systems engineering—to see to it that all the pieces fit together and that the overall capability is the best that can be achieved on a reasonable schedule and at reasonable cost. Attention to the interoperability of the various systems that constitute an overall mission system capability is an important part of MITRE's systems engineering work.

Many groups other than the user command and the system program development agency are involved in these programs. In each of these agencies, many different people have a voice on the program, and there is considerable turnover in these personnel over the life of a typical acquisition program. Congress approves funding, and congressional staff are especially active in trying to understand each program. They advise the members of Congress on plans for new programs and on the progress or lack of it on existing programs. Congressional action may have profound impact on a program—it might be canceled altogether, for example.

Congressional actions may have very substantial impact without being lethal, however. For example, when funds are cut and production rates are substantially reduced, as happened with AWACS, the unit cost goes up dramatically, and the planned total buy may have to be reduced with corresponding impact on the capability available to the user. Later in the program, those who are uninformed about the background want the development agencies to explain why unit costs went up, or why they did not deliver the total fleet. This is one of the hazards of the business. As systems engineer, MITRE must be continually alert to the actions of Congress and the many other DOD and service groups as they might affect the program. Further, the Corporation must advise the program director on actions required to avoid undue impact on the program by other agencies. When changes are directed, MITRE must help the program director make them while minimizing the impact on the capability achieved, schedule, and cost. To accomplish this responsibility, it is important that MITRE

interact with the key people in government and industry. Insights gained in this way can be very useful in helping to formulate advice that the Corporation gives to a program director on how to handle a particular problem or opportunity that may arise on the system acquisition program.

Many of the changes that the environment forces on a program are less obvious than those that result from congressional funding cuts. However, their impact on performance, schedule and cost can be just as serious. The government may impose new message standards or new communications protocols on the program. Each action may be a good thing to do, but might have tremendous impact on an existing program.

When changes are necessary, for whatever reason, MITRE must work with the other program participants to identify the modifications in the program that must be made. One very important consideration is the existing industrial contracts. Which ones must be changed and how? This area can be a major impediment to rapid reaction to required change. Among the other questions to be answered by the participants are: What is the impact on system performance? What are the schedule and cost implications? Too often, in a rush to be responsive, one tries to accommodate directed changes within the existing program. MITRE must recognize when such an approach will result in less system performance or more time and money. Directed changes that have significant impact on the program need to be so identified and their performance, cost, and schedule implications clearly described at the time the changes are directed. The interest here in early identification of the impact of change is not to say, "I told you so" later. Rather, it is in the interest of identifying what should be done to make the best of the situation early enough to avoid undesirable compromises in capability, schedule, or cost. It is simply the professional way for MITRE to conduct itself in its dedication to achieving the capability. When necessary, the Corporation should work with the program director to have his or her direction and funding modified to be consistent with the change being imposed.

MITRE must interact with key people in government and industry. Insights gained in this way can be very useful in helping to formulate advice that the Corporation gives to a program director.

In accommodating change, one should also consider the possibility of packaging a number of individual changes together. Preplanned "block" changes may have advantages in both the operational and acquisition areas. A system that is in a constant state of change tends to lose operational effectiveness. Similarly, changes that are made individually are more costly and take more time than those implemented as a package. Program stability may be more important than responsiveness. MITRE should keep this possibility in mind in providing advice to the system program director on dealing with potential changes.

Directed changes that have significant impact on the program need to be so identified and their performance, cost, and schedule implications clearly described before implementation.

Obviously, agreements among all the parties are not achieved once and then honored for the life of the acquisition program. Many of the persons involved change over time and the new people do not necessarily think the same way as their predecessors. As systems engineer, MITRE must continually be tuned to changes in key personnel in other agencies and to the potential impact of those changes. Realistically, there are many other factors that may require changes in the program. As noted above, funding may change. The Corporation must be prepared to recommend what action should be taken as a result, with all things considered. But other important things change, too. Perhaps the threat has changed, or perhaps the available technology has improved to such an extent that the program should modify its technical approach, or maybe what was being attempted was too ambitious and needs to be cut back. MITRE has access to government threat information not generally available to contractors. With that access comes the responsibility to be sure the nature of the threat is continually assessed and the impact of it reflected in the program in a timely way.

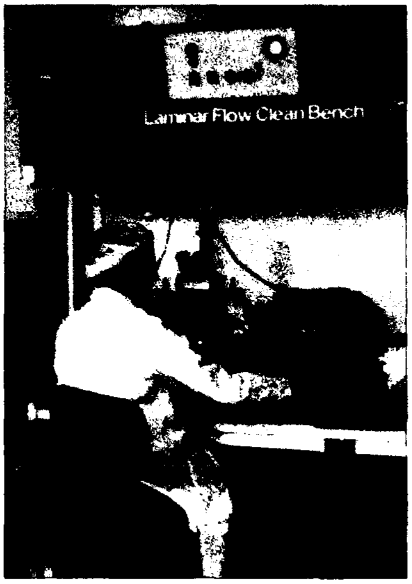
Similarly, MITRE is a key technical player on the government side with regard to available technology and its application to the program. The Corporation evaluates the technical progress being made on the program, continually assesses new technology that may be coming available, and estimates its potential use on the program. The concern for technical progress and the knowledge of potentially applicable technology are two major thrusts of MITRE's systems engineering work. These two areas must be monitored closely by

MITRE throughout the life of a program. Further, the Corporation must take the initiative with the program director to be sure that their impact on the program is both understood and accommodated when appropriate. However, one must resist the allure of new and potentially risky technology when the available technology is adequate for the purpose.

Another aspect of the environment in which an acquisition takes place is the competition that exists among development programs. Even a program that is providing the necessary capability on schedule and at planned costs is not exempt from this competition. As everyone appreciates, defense programs are in competition for funds with other government needs, such as social services. Within the money available for defense, there are many conflicting demands. Again, agreements made last year may no longer hold this year. This is the nature of the business and as systems engineer, MITRE must help the program director anticipate, avoid, or react to changes that affect the capability to be delivered.

Clearly, the earlier in a program that the need for change is recognized, the better. The longer a program proceeds down a certain path, the more entrenched people will get in what they are doing and the more difficult it will be to persuade them to change. Also, the more resources are expended in a certain direction, the more that may be wasted if that direction is changed. MITRE should not only understand what is happening at any given time on a program, but also extrapolate ahead. Anticipating the need for change, and the earlier the better, is a key MITRE role.

Suffice it to say that the environment within which a system acquisition program takes place is very complicated. Understanding that environment in a firsthand way and reflecting it in the advice given to the system program director are major MITRE systems engineering responsibilities. Being expert on the details of the program in question is not enough. To be effective, the technical staff at MITRE must put its immediate work in the larger, real-world context.



Monolithic Microwave Integrated Circuit Laboratory

MITRE's Qualifications and Approach

The MITRE Corporation is uniquely qualified to perform as systems engineer for some of the government's most challenging C^3I acquisition programs. As discussed in this chapter, MITRE's uniqueness is derived in part from its corporate form, a highly qualified technical staff, and a deep appreciation of the operational capabilities desired by the government. The Corporation's 35 years of experience in the systems engineering role and the dedication of the management and staff to achieving the required systems capabilities are other factors in that uniqueness. The chapter concludes with a review of how MITRE's background and experience are applied to some of the more sensitive systems engineering issues that arise on almost every C^3I systems acquisition program.

Corporate Form

MITRE and the Air Force have a special relationship. The Corporation was formed in 1958 by the Massachusetts Institute of Technology (MIT) at the request of the Air Force, after it was determined that the people at MIT's Lincoln Laboratory were uniquely qualified to assume the system engineering role for the nationwide implementation of the SAGE continental air defense system. Lincoln Laboratory

was responsible for the initial design of the system, and as the system moved into a production and implementation phase, MIT recommended that subsequent system engineering responsibility be transferred to a non-academic institution.

Building the SAGE system involved almost every major defense contractor in the United States. In looking for an alternative to MIT for SAGE system engineering, the Air Force recognized that the system engineering organization could not carry out that role without potential conflict of interest if the organization was also eligible for contracts to build parts of the system. Since the industrial defense contractors had profit as a meaningful motive, and since the highest chance for profit was in manufacturing, not system engineering, major industrial firms declined to accept the system engineering role under the Air Force requirement that they could not both assume that role and continue to build portions of the system.

After considering a variety of industrial, governmental, and other alternatives, the Air Force concluded that only the people at Lincoln Laboratory were qualified to carry on the SAGE work and asked the university to help them retain that talent. In response to that request, MITRE was formed under the sponsorship of the Air Force. Significant numbers of the Lincoln Laboratory personnel who had been working on SAGE transferred to the new corporation in January 1959. In part, then, it was the uniqueness of the knowledge and skill of the people involved that led to the formation of MITRE.

MITRE's unique, long-term relationship with the Air Force on systems engineering for C^3I systems was reaffirmed in 1985 in a sponsoring agreement signed by the Commander of the Air Force Systems Command and the Chairman of the MITRE Board of Trustees.[42] Over time, the Corporation's role—with the Air Force's support—has been extended to similarly serve other parts of the government, as well.

[42] *Basic Principles Governing Air Force MITRE Relationships*, October 23, 1985.

The rules under which the Corporation operates were formulated in the very beginning to permit performing in the unique systems engineering role. MITRE configured itself to minimize the chances for, or appearances of, conflict of interest either for the Corporation as a whole, or for individual staff. All parts of the Corporation's operation are open to government review. MITRE personnel are appropriately constrained with regard to personal outside activities. As a nonprofit corporation, MITRE does not pay taxes on its income. But MITRE is also a not-for-profit corporation, a term used to make clear that by charter and contract MITRE does no manufacturing, will not accept work from commercial or industrial organizations, and will not formally enter bid competitions with profit-making corporations. These factors permit MITRE to operate in as conflict-free a way as possible. They are not limitations; they help the Corporation to be effective in the systems engineering role between government and industry.

Over the last 45 years, a set of formally recognized organizations devoted to public affairs and run either privately or by universities, has come into being. They now represent about five percent of the government's total research and development (R&D) budget. In 1968, the President's Office of Science and Technology officially designated such organizations as Federally Funded Research and Development Centers (FFRDCs). The DOD had previously chosen to refer to the FFRDCs for which it was responsible as Federal Contract Research Centers, or FCRCs. In 1984, the Office of Management and Budget (OMB) in the Executive Office of the President of the United States issued a policy letter formalizing FFRDCs as a new source for federal R&D, adding to the three existing sources: industry, academia, and the government itself.

The part of MITRE that works on DOD C^3I systems is an FFRDC. The implications of being an FFRDC are amply and well discussed in a MITRE paper by Dr. Norman Waks.[43] In fact, MITRE has always operated in such a way that it fulfilled OMB's criteria for an FFRDC,

[43] N. Waks, *The Uniqueness of the MITRE Corporation*, M87-15, The MITRE Corporation, Bedford, MA, March 1987.

even before the category was established. From the beginning, MITRE was specifically constituted in ways that made it possible to fulfill the Corporation's conflict-free systems engineering role. The original MITRE charter called for the Corporation to operate "in the public interest." The Corporation had been performing R&D work for the government since 1959. Therefore, when such categories were established, MITRE became both an FFRDC and an FCRC. To further narrow the class of corporations to which the Corporation belongs, only two of the FCRCs perform in the systems engineering role: MITRE for C^{3}I systems for DOD, and Aerospace Corporation for systems developed by the Space Systems Center of the AFMC. The other FFRDCs fall into two other categories: R&D laboratories or Studies and Analyses Centers. MITRE's corporate form and work area are unique among industry, government, academia, and even the other FFRDCs/FCRCs.

The government contracts with MITRE through directed awards, based on the Corporation's unique qualifications to carry out the required work. Avoiding the need to compete is not the purpose of directed awards; directed awards are used because the government will not permit MITRE to enter formal competitions. By refusing to permit MITRE to bid against profit-making industry, the government protects and reinforces MITRE's conflict-free status. The awards directed to MITRE may be based on a sole-source determination in which the government establishes the best possible source for the professional service and then directs the award to that source. Although MITRE does not formally compete, clearly the Corporation must be competitive—in technical capability and cost of doing business—to be uniquely qualified.

Avoiding the need to compete is not the purpose of directed awards; directed awards are used because the government will not permit MITRE to enter formal competitions.

As an independent contractor, MITRE is neither part of government nor part of industry. As noted by Dr. Waks, in 1972, the congressionally-initiated Commission on Government Procurement recognized the "independent perspective" of the FFRDCs and cited the government's need for FFRDCs to "look over its [the government's] shoulder" in areas of great consequence. The government

wants MITRE's best advice, and the Corporation is dedicated to providing it.

As noted in Volume 1 of *Quality Assurance at MITRE*,

> *Tasks to be accomplished by MITRE are assigned only when the role is appropriate. MITRE is not used if an appropriate government capability exists or if industry can do the job as effectively and without conflict of interest.*[44]

Specific criteria applied by the government in deciding whether to assign work to MITRE are described below. The above reference goes on to note that this sort of scrutiny helps ensure a technically challenging and important work program for MITRE. Rather than viewing this process as a limitation on what MITRE may do, one should appreciate that it forms the foundation for the strengths of the Corporation. It is also the foundation for the special relationship that exists between MITRE and its sponsors, including the Air Force.

The character of the MITRE work covered by the contract with ESC is described in ESC Regulation 80-1 (ESCR 80-1). This document describes MITRE as an independent contractor, responsible for the management of its own affairs, and notes that this independence is necessary for the Corporation to maintain the objectivity valued by the government. System engineering is called the preferred MITRE role, and in this role the regulation states that MITRE will:

> *(a) take broad initiatives on all technical matters pertaining to the program;*
>
> *(b) provide positions on all technical matters of interest to the Government Program Manager;*
>
> *(c) adopt a broad view transcending the strictly technical aspects that contribute to a program decision; and*
>
> *(d) keep the Program Office advised of its activities.*[45]

ESCR 80-1 then goes on to discuss typical systems engineering activities. It also notes the sort of tasks that should not be assigned to MITRE;

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[44] *Quality Assurance at MITRE*, Vol. 1, M88-39, The MITRE Corporation, Bedford, MA, 1988, p. 7.

[45] *Utilization of MITRE Support*, ESC Regulation 80-1, December 1991.

for example, MITRE is not to be used for routine technical, administrative, or management tasks, and use of MITRE staff to augment the Air Force technical staff is specifically precluded. More precisely,

> *MITRE is assigned responsibility for specific jobs it has contractually accepted and will not provide personnel for assignment and direction by the government.*[46]

ESCR 80-1 also reiterates and expands on the criteria to be used in determining the appropriateness of a piece of work for assignment to MITRE to include:

> (1) *freedom from bias due to preference in design, hardware, or approach;*
>
> (2) *need for industry proprietary information;*
>
> (3) *access to industry proposals;*
>
> (4) *need for extensive background information;*
>
> (5) *need for state-of-the-art information from government laboratories;*
>
> (6) *access to Air Force planning information;*
>
> (7) *access to intelligence;*
>
> (8) *need for outstanding specialists in specific fields;*
>
> (9) *need for diversified skills;*
>
> (10) *performance of technology base functions;*
>
> (11) *continuity of effort;*
>
> (12) *need for special facilities and*
>
> (13) *need for fast response*[47]

MITRE's contract, which covers many projects, is between the Corporation and the government agency, not between the project leader and the government program director.

Each of these areas is described further in the regulation. These criteria serve to ensure that MITRE is properly used by the government and, since the MITRE resource is limited, help to ensure that the Corporation is employed on the most demanding government programs.

As mentioned in Chapter 3, MITRE's work on important government programs is organized into projects; for each project, there is a

[46] *Utilization of MITRE Support*, p. 8.

[47] *Utilization of MITRE Support*, pp. 10-12.

project leader who supports a corresponding person in the government, usually called the program director or project officer. The project leader is responsible for the day-to-day activities of MITRE personnel assigned to the project. For a typical project, the MITRE responsibilities are delineated in the TO&P. Each TO&P is incorporated by reference in the formal contract between MITRE and the government agency involved. The contract, which may cover a large number of individual projects, is between the Corporation and the government agency, not between the project leader (as a representative of the Corporation) and the government program director.

MITRE's management is an active participant in the work done on each project. Project planning must provide time for their reviews and for actions that stem from those reviews.

MITRE does not contract for the personal services of its staff; rather, the Corporation contracts for the products described in each TO&P and agrees to provide those products under the terms of the relevant contract. The project leader and the other personnel assigned to work on the project are responsible to corporate management for accomplishing the work described in the TO&P. The Corporation is responsible for delivering the required products under the terms of the contract.

In addition to selecting a capable project leader, management above the project leader has a responsibility to ensure that appropriate personnel are assigned and that adequate resources are available to carry out the work. Management must also agree that the work to be performed is appropriate for MITRE. Management has the normal responsibility for in-process review of the work to ensure it is responsive to the customer's needs and satisfactorily performed. MITRE's management is an active participant in the work done on each project. Project planning must provide time for their reviews and for actions that stem from those reviews.

MITRE is willing and very quickly able to modify its work program when requested to do so by the Air Force. The Corporation has experience in most areas of C^3I of interest to the United States. When requested, with an absolute minimum of negotiation and paperwork, MITRE can quickly reduce work in one area to assume higher priority work in another one.

Since there are government-imposed controls on the rate of growth of MITRE, and natural controls on such growth in any case, one finds that the specifics of the MITRE work program are constantly changing in response to ESC needs. The rate and the extent of these changes are far beyond what could be handled through normal, competitive industrial means. This would be so even if industry were willing and able to meet all the other constraints placed on MITRE. The required changes are facilitated by the management processes used by ESC and MITRE. They are possible because of the breadth and experience of the Corporation's staff.

MITRE must be vigilant about the quality of the work performed and about the cost of its own operation.

MITRE's designation as an FFRDC does not relieve the Corporation from many of the challenges that face any business or industry. The Corporation has no guarantee of work from any government organization. As an FFRDC, MITRE will not enter bid competitions with industry. The Corporation's viability as a systems engineering organization is based on the quality and cost of the work it performs. The Corporation is subject to all the market forces that govern the establishment of a quality work force at competitive costs. To attract a quality staff, the work must be challenging and rewarding, the facilities matched to accomplishing the work, and the salaries and benefits competitive with industry. To be competitive with other sources of systems engineering, the work must be well done and the costs as low or lower than potential alternatives for equivalent work. MITRE must be vigilant about the quality of the work performed and about the cost of its own operation.

In most cases, MITRE is funded by an agency that is responsible for development of a system or capability. A program director (or an analogous person) is the agency representative responsible for the day-to-day conduct of the development program, including the MITRE work on that program. Clearly, MITRE must respond to the needs of the program director. The development agency is responsible for delivering the system to a user who will combine the system with other existing ones, and perhaps new systems, to achieve a required operational capability. In some sense, then, the user is the ultimate

customer of both the project officer and MITRE. At the same time, there is an organizational hierarchy within the government that has individual development agencies reporting through a series of levels to a service headquarters, for example. The project officer is responsible for satisfying the demands of these groups, as well as for meeting the needs of the user. MITRE is responsible for helping the project officer to do that.

MITRE knows it has clear obligations to the program director, that the program director provides the funds for systems engineering, and that the program director has the ultimate responsibility for meeting the user requirements. The MITRE contract covering the work performed for the Air Force is issued by ESC. Each acquisition program director decides what work he or she would like MITRE to do, negotiates the terms of that work with MITRE, and provides the necessary funding to ESC for application to the MITRE contract. As a result, the Corporation has an obligation to ESC, to AFMC, and to each of the individual program directors for the performance of the work defined in the contract. MITRE believes that meeting these responsibilities requires direct interaction between MITRE staff and management personnel and their counterparts in these agencies and in industry.

MITRE's articles of incorporation state in part that the Corporation was formed to perform scientific and engineering services to enhance the security of the United States and to otherwise further the public interest. MITRE's Board of Trustees is responsible for ensuring that the Corporation acts accordingly. The Board actively reviews the work that MITRE proposes to do before that work is accepted, to be sure it is in the public interest and appropriate for an FFRDC. For the same reasons, the Board also does in-depth reviews of the manner in which the contracted work is performed, with particular interest in the quality of that work. These reviews affect what MITRE does and how.

MITRE's management is committed to ensuring that the Corporation effectively meets both the explicit requirements of the TO&P in support of each program director, and the implicit commitments to

higher headquarters and to the user. Management is also responsible for ensuring that appropriate resources are assigned to each program and that those resources effectively deliver the products described in the TO&Ps. To do that, management must be well informed on each program and must use its experience and knowledge to direct the work of the staff.

As described in Chapter 3, each program is conducted in a very expansive and volatile environment. It is therefore important for management to ensure that the staff is well informed on all factors that may have an impact on the success of an acquisition program. In turn, this dictates that management interacts with others in industry and government who may have insights useful to the program. Given that such interactions are important to ensuring the efficacy of the MITRE work, it is clearly incumbent on management to ensure that such interactions take place in ways that do not undermine—or even appear to undermine—the Corporation's contractual obligations to the program directors and to ESC. This is a delicate task for management that requires the understanding and good faith of all parties. This interaction between MITRE management and others in government and industry can be a very effective tool available to help program directors conduct their programs successfully.

MITRE believes it has obligations to ESC, and to higher headquarters, that transcend the specific requirements of the individual TO&Ps incorporated in the contract with ESC. The Corporation is dedicated to meeting these obligations without compromising its systems engineering work on individual acquisition programs.

Maintaining a Skilled Technical Staff

Both broad system knowledge and in-depth technical expertise in many areas are required for effective systems engineering. One does not necessarily expect to find both in the same person and sometimes not even in the same organization. However, MITRE has both skills. In many organizations, there are groups that are clearly franchised as technical and somehow distinguished from project personnel. At

MITRE, some staff is assigned to the technical centers, but the majority of the staff is not. Also, at any given time, most of the staff of the technical centers is assigned to work on acquisition projects for which MITRE has the systems engineering role. Whatever organizational approach one uses, there is conflict between those who tend to consider the technical first and everything else second, and those who feel that the demands of the project may require some compromise in the technical area. This conflict sometimes results in project personnel being referred to as generalists. The implication is that the generalist has less technical skill. There is, of course, no a priori reason for that to be so. An interesting quotation on this subject is found in R.E. Machol's book:

The Corporation is not merely providing the services of a set of people with technical skills; it provides corporate systems engineering support dedicated to achieving the required capability and provides that support through skilled technical people.

> *The system engineer must be a generalist as distinguished from a specialist, but he must not be a dilettante. The ideal system engineer is . . . "T-shaped". . . broad, but deep in one field; the depth is provided by scholarly experience.*[48]

MITRE as a corporation is dedicated to maintaining the highest level of technical competence possible to fulfill its systems engineering role for the government. High technical competence is required if MITRE is to "take broad initiatives on all technical matters pertaining to the program" and to "provide positions on all technical matters of interest" as required by ESCR 80-1. That is an awesome task when one considers the wide range of systems for which the government has asked MITRE to assume systems engineering responsibility. It is also one that the Corporation takes very seriously. It is a major factor in the Corporation's approach to systems engineering. The success of MITRE's systems engineering is measured by the quality of the system that results. The Corporation is not merely providing the services of a set of people with technical skills; it provides corporate systems engineering support dedicated to achieving the required capability and provides that support through skilled technical people.

[48] R.E. Machol, *System Engineering Handbook* (New York: McGraw-Hill, 1965), pp. 1-11.

Among MITRE project personnel, one finds all three of the essential ingredients of successful systems engineering: in-depth understanding of and appreciation for the needs that the system is to satisfy; current knowledge of and the skill to apply the appropriate technologies; and a persistence and ability to apply these two skill areas in the real world for the achievement of the needed capability.

The quality of the MITRE staff is inextricably intertwined with the quality of the MITRE work program. High quality work attracts and retains highlv skilled people. Highly qualified technical personnel attract challenging work. As discussed earlier in this book, there are a series of checks made by the government and the Corporation on each new piece of proposed work to be sure that work is appropriate for assignment to MITRE. Those checks help to ensure a high quality work program. As will be discussed, the Corporation has a number of mechanisms to ensure that the quality of the staff matches well with the challenge of the work program.

The corporate-wide efforts to maintain a high quality technical staff are discussed in some detail in a MITRE paper on how the Corporation achieves quality assurance on the work of the staff.[49] These efforts have many dimensions. One concerns the hiring and retention of skilled technical personnel. The data provided in Volume 2 of the quality assurance paper indicates that MITRE is a balance of experienced and newly trained technical personnel. The number of staff is approximately equal for each 5-year increment of years of experience from 0–4 years to 20–24 years. Those with more than 25 years of experience number about twice the size of each of these 5-year groupings. Over 70 percent of the staff has more than 10 years of experience. This mix of experience levels provides a balance between experience and recent education and training that is well suited to helping MITRE's customers exploit the latest technology.

In the past, MITRE has increased the size of its professional staff to satisfy the government's requests for additional systems engineering

[49] *Quality Assurance at MITRE*, Vols. 1 and 2, M88-39 and M88-40, The MITRE Corporation, Bedford, MA, October 1988.

support. In that process, the Corporation's hiring standards have remained high. Less than one percent of the resumes submitted to MITRE result in the person being hired. Over 60 percent of those hired come from industry and provide the latest in industrial experience, while approximately 15 percent are new college graduates trained in the newest available technologies.

Well over 50 percent of MITRE staff has advanced degrees and the mix is representative of systems engineering tasks, as opposed to what might be required in a research laboratory. The degree fields included span all those necessary for MITRE's systems engineering work including electrical engineering, other engineering, computer science, the physical sciences, and mathematics.

The high demand for the Corporation's services has been one indicator of the quality of its staff. However, there are others. Each year, MITRE publishes a set of documents that record the professional activities of the staff, including those that are outside the work done directly on a customer project.[50] These include membership in professional societies, publications, participation in technical conferences, work on standards and other committees, teaching appointments, and honors and awards. The accomplishments reflect well on the technical ability of the MITRE staff. This sort of recognition of MITRE people in the general professional community is another indicator of the high quality of the Corporation's technical staff.

In addition to attracting high quality staff, the Corporation also does a number of things to retain that staff and to keep it current on the relevant technologies. The MITRE Institute provides for continuing education for all MITRE employees. Under this corporate-sponsored program administered by the Institute, all employees are eligible for educational assistance through external courses at accredited institutions. The Institute also provides a number of in-house courses that are designed to meet MITRE's unique needs and are unavailable elsewhere. Other Institute activities include courses in

[50] *Summary of Professional Activities - Center for Air Force C³ Systems*, M92 B0000071, The MITRE Corporation, Bedford, MA, 1991.

professional development, management development, project budgeting, and technical documentation.

Under the Institute, the Corporation sponsors a Masters Degree Program in Science and Engineering and offers extensive on-site availability of televised courses from universities local to MITRE's major locations. The MITRE Institute also sponsors a Distinguished Lecturer Series in which distinguished individuals from the professional and scientific communities make presentations at MITRE on subjects that both stimulate the technical skills of the staff and broaden the context within which the staff makes technical judgments. Recently, the Institute initiated another program, the National Defense Series, in which senior people from outside of MITRE provide the staff with perspectives on national defense issues and plans important to the MITRE work.

A second major corporate approach to maintaining the technical strength of the staff is the MITRE Technology Program. The MITRE Technology Program is partially funded from fee under the MITRE Sponsored Research (MSR) Program and partially from separate sponsor-funded technology projects. Some technology work is also done as part of the systems engineering projects. Approximately 10 percent of MITRE's volume is dedicated to technology work. Management identifies key general technology areas to be pursued and specific proposals are sought from the staff in those areas, as well as others. Management chooses from the proposed projects. Some are then funded by the sponsors and the remainder are supported by MSR funding. A strong in-house technology program provides opportunities for the staff to stay current and to contribute to the state of the art. Challenging technical work also helps to attract additional high-quality professional staff.

Another corporate method for attracting and maintaining a high quality technical staff is the use of an alternative promotional path for people who would prefer not to assume management responsibility but would like increased technical responsibilities within the Corporation. The technical promotional path has positions of

responsibility corresponding to those of the management ladder within MITRE. It serves to provide paths for advancement for highly qualified staff members who have made significant contributions to MITRE's work, attracts and retains outstanding technical contributors, and improves the quality of technical work performed by MITRE. Members of the technical ladder at all levels are expected to make significant contributions to MITRE's systems engineering projects.

Other corporate mechanisms for ensuring the quality of MITRE's technical staff include information exchange programs with government, universities, and industry. Personnel from these groups visit MITRE to see its work, and MITRE personnel make reciprocal visits to government, university, and industry locations. The Corporation also sponsors symposia or large conferences each year on topics of interest to its sponsors and to related industry. As already noted, MITRE staff members belong to professional organizations, regularly publish papers in professional journals, and participate in special government studies.

Finally, MITRE has adopted a number of organizational mechanisms designed to improve the quality of the technical work on the acquisition programs. The Corporation cannot afford to maintain large numbers of skilled technical people in each of the technical areas represented by the programs for which it has systems engineering responsibility. Optimum use of the technical resources across MITRE's projects requires special management attention. In a modified matrix structure, staff who are experts in the major specific technical fields such as sensors, software, networks, etc., are assigned to a corresponding technical center. The center directors in turn use these resources to provide support to the acquisition projects. This approach increases the flexibility available to management, since critical skills can be applied more easily where they are needed at any given time. It improves the technical quality of the acquisition project support, since the management of the technical centers is involved in the work and its review. The approach helps to establish a critical

mass in the technical areas and to make it possible to provide special tools to the groups that could not be provided if the groups were dispersed. Finally, this approach makes it easier to attract top technical people to MITRE.

Related to the technical centers, the Corporation also has a number of smaller technical groups for staff who are expert in some of the technical areas not included among the major technical centers. These groups are officially recognized by the Corporation and promote structured communication, networking, and mutual support.

This section has provided a very brief summary of the MITRE activities designed to provide a highly qualified, professional technical staff in support of the Corporation's systems engineering responsibilities. It is a challenge that MITRE management has taken very seriously, and one they will continue to ensure is successfully met. Such a staff is one essential ingredient of the Corporation's systems engineering work. A second important ingredient is the subject of the next section of this book—a technical staff with deep understanding of the operational capability that the government is attempting to achieve.

Developing Staff Knowledge of Operational Capabilities

For the Corporation to be successful, the MITRE systems engineer must have a deep appreciation for the operational capability that the government needs—a thorough, personal understanding—not just a statement of what someone else may say it is. Before suggesting how the staff is able to achieve such an understanding, it may be helpful to describe, in some detail, the extent to which the staff must understand the need and how that understanding is employed in the day-to-day systems engineering activities.

Earlier in this book, it is observed that the government tends to buy subsystems—a radar, or a piece of communications equipment, or a command center. The development community provides the subsystems to a using command that must combine them with other existing subsystems and turn the collection into an operational mission capability, such as air defense or finding and killing ground

targets. MITRE has had systems engineering responsibility for most of the command and control-related items that have been produced over the last 35 years for the Air Force. An indication of the span of the Corporation's C^3I system activities may be found in a review of its first 30 years.[51] This paper lists well over 100 different C^3I systems for which MITRE has had systems engineering responsibility.

In the systems engineering role, the Corporation has worked at operating field locations and helped to make the systems function to achieve mission capabilities. MITRE has also had staff assisting in this process at major user headquarters locations. In both the development and operational phases, the Corporation has assisted in providing effective interfaces among the systems of the various military services and with systems of other friendly nations. As a result of this background, within the development community, MITRE has a unique appreciation for the capabilities that the government is trying to achieve. This observation is not a negative reflection on any other organization; it is simply a statement that MITRE has had opportunities to understand the essence of system capabilities, over longer periods of time, and from more perspectives than any other organization, industrial or military. Neither is the statement meant to confuse who is responsible for achieving military capabilities—the operational using commands. It is also not meant to cloud the clear responsibilities of the military service development agencies. The statement merely means that one of the key foundations of MITRE systems engineering work is a profound appreciation for the capabilities to be achieved and a deep dedication to doing what is necessary to achieve those capabilities.

As a result of its background, MITRE has a unique appreciation within the development community for the capabilities that the government is trying to achieve.

Some further discussion here is necessary to provide insight into the levels at which MITRE understands the capabilities that the government is attempting to achieve. Air defense will be used as an example. Everyone in the business has an idea about what is meant when someone says they want an air defense capability—a capability

[51] *The MITRE Corporation, Challenge and Response, 1958–1988*, The MITRE Corporation, Bedford, MA, 1988.

to know one is coming under air attack and a means to destroy the attackers before they can damage the defended area. At the next level, one begins to assess the characteristics of the threat and those of the existing friendly forces available to deter that threat. How many threat aircraft, and what are their range, altitude, speed, and weapon-carrying capabilities? Do they have standoff capabilities? When one begins to understand how difficult the problem might be, another round of questions arises on what one means by air defense in this case.

Do we merely mean to maintain sovereignty of our air space, with the implied admission that the system could not handle any substantial air attack, or are we intent on being able to provide substantial defense against a determined enemy? What is meant by substantial? How big are the attacks apt to be? How much damage are we willing to accept? Does the defense have to be perfect, or only able to handle some major portion of the threat? How much robustness should the system have? Are multiple attacks expected? Questions of this sort are many. The answers drive the development programs in a first-order way. However, the answers are not easy to come by. Many of the people involved do not have the background to answer them, and important people disagree on their views. Nevertheless, questions such as those above are typical of many that MITRE considers in the systems engineering role.

In addition to the questions on broad operational requirements, there are those related to cost, and to the priority among the many competitive demands for government funding both within DOD and between DOD and other government programs. How much are we willing to spend on air defense? Both acquisition costs and the ownership costs are important. What types and numbers of operational and maintenance personnel may be made available for the system? What are the logistics support implications? Can the air defense assets contribute to other mission areas if need be? Debates begin to arise over whether one gets more air defense for the money by investing in new weapons, sensors, communications, or command and

control centers. The politics of what is built in a particular congressional district may impinge on the debates. Other non-technical matters will arise as issues.

How much capability do we already have? What will be provided by other development programs either in progress or planned for the future? Will other systems provide early warning of attack? How does one distribute the capability among the subsystems? Are the subsystems that program direction says to acquire those that will provide the best capability for the funds available? As one proceeds down a path such as this, fewer and fewer groups have the background or the responsibility for addressing such questions. Yet in its systems engineering work on subsystems associated with air defense, MITRE considers such global matters, as well as many other more detailed questions.

As an example, to provide air defense, one must know when enemy aircraft are approaching the defended area. The system must be able to keep track of them as they approach and as they are engaged by friendly forces. Sensors, typically radars, report where the aircraft are located and computers use that data to perform the air defense function known as automatic tracking. However, the demands on the automatic tracking function vary greatly as a function of the threat and the weapon system capabilities. Many other questions arise concerning the threat. How high or how low and how fast will the enemy aircraft fly? What maneuver and jamming capabilities will they have? Other types of questions must be considered. At what point in the intercept and with what accuracy does the tracking function have to provide data to the weapon platform? To make matters worse, the answers may vary dramatically over time as both friendly and enemy force capabilities evolve.

MITRE staff must understand how the automatic tracking relates to other system functions. Ultimately, air defense gets down to destroying enemy aircraft before they destroy whatever is being defended. One requirement for automatic tracking is that it must provide the location of the enemy aircraft with an accuracy sufficient

to permit friendly weapons to kill the enemy target. But the accuracy required may be very different, depending on whether the weapon is a manned aircraft or a surface-to-air missile. And the capabilities of the manned aircraft weapon system may vary widely. At one point in history, the computer-generated position of an enemy aircraft needed to be highly accurate to successfully guide the friendly weapon to attack it. Today, the weapon systems themselves have significantly greater capabilities to do the weapon guidance in the final phase of an attack. As a result, the demands on the accuracy of the tracking function are significantly less. MITRE staff must continually ask, "Why is this function being performed? Under the circumstances that exist in other parts of the overall capability, what are the performance requirements on this function?"

But MITRE's knowledge and understanding of air defense extends far deeper than the global issues or the functional design questions illustrated above. At the opposite end of the spectrum, the Corporation's work may even demand that the staff understand the meaning of the individual bits deep within the computer program.

Again as an example, at one time the Air Force established a requirement to interface two systems that were operating in Europe and that had not been designed to work with one another—the NATO Air Defense Ground Environment (NADGE) system and the 407L Tactical Air Control System. NADGE had been acquired by NATO and 407L by ESC. MITRE wrote the original specification for NADGE and participated in its acquisition. MITRE was also the system engineer on the 407L program. The desired interface was to provide for computer-to-computer exchange of the information on the aircraft being tracked by each system. To complicate matters, the using command wished to have the new interface capability operational in less than a year. In view of the short time available and the Corporation's background on both systems, it was only natural for the government to come to MITRE for help in interfacing these systems. The depth of MITRE's knowledge was illustrated not just

by understanding the electrical characteristics of the two systems or their different tracking logics. MITRE staff was familiar with the different nomenclatures used by the two systems when referring to different classes of enemy aircraft and even knew which bits in the computer messages were used to convey those nomenclatures. This background, broad and deep in both systems, permitted the Corporation to provide an initial version of the necessary interface system in a timely way to meet user requirements. Later, the initial MITRE development models were replaced by industry production systems.

MITRE staff in the systems engineering role must, as a group, have equal facility from the bit level in the computer program to the global issues that surround the associated capability.

The examples of the range of MITRE's activities in an operational mission area presented above have concentrated on air defense. The point of this discussion is simple but profoundly important: In addition to being technically competent, MITRE staff in the systems engineering role must, as a group, have equal facility from the bit level in the computer program to the global issues that surround the associated capability. When we say MITRE understands the capability that the government wishes to achieve, we mean to cover this entire range. MITRE expertise of this sort exists not only in air defense, but also in many operational areas, including other strategic missions, tactical operations, and intelligence information processing. Since these mission areas often intersect, the strength of MITRE and its ability to assist in achieving DOD capabilities are reinforced by the Corporation's knowledge and experience across the entire spectrum of DOD C^3I systems.

Assuming the staff has the necessary understanding of the system capabilities needed by the government, how is that understanding applied in the systems engineering role? Successful completion of complicated acquisition programs requires continuous and careful management by the government. A program often does not proceed exactly as originally planned. Difficult questions may arise at many different times during the life of the program. They will always arise in circumstances where there is a set of apparent givens—requirements statements, program direction, contracts, design decisions, resource commitments, and the like. They will always occur in a

setting where important people have differing opinions about what action to take, if any. Some will prefer to wait and see what happens, rather than take an action that later others can say caused a problem rather than solved one. System performance, time, and money will almost always be factors. The preferred technical solution will not match the real-world needs or politics. Egos and reputations may be at stake. Presumably, as systems engineer, MITRE will have an opportunity to suggest appropriate action. How does the Corporation decide what to recommend?

It is assumed here that MITRE is a full partner in the program in the way described earlier. The MITRE staff knows in a special way what the user is trying to achieve, is fully informed on all aspects of the situation, and knows what is technically and otherwise feasible. No matter what stage the program is in, from early conception to field operation, and no matter the surrounding circumstances, MITRE people must continually ask themselves, "What is the best thing to do at this time, everything considered, to achieve the needed capability on a reasonable schedule and at a reasonable cost?"

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This question, and its answer in any particular case, perhaps more accurately than anything else in this book, describes the attitude and contributions of MITRE in the systems engineering role. The Corporation is dedicated to helping the government achieve the required capability, is knowledgeable and current on as many of the relevant factors as possible, and is prepared to recommend appropriate actions.

The informed answer to this question provides guidance during normal program times. When the situation on a program gets truly tenuous and contentious, the knowledgeable answer to this question is the only useful way for the MITRE staff to decide what to recommend. The program direction should be considered in answering the above question, but if getting it changed is the best thing to do, MITRE should so recommend. The situation may dictate that some compromise in the stated requirement is necessary to achieve a needed capability. The contracts the government has with industry are important and they should not be treated lightly, but if they need to be changed, the

Corporation should recommend it. The argument about which organization should pay for the change, or how much money the government should get back, or whatever, is a separate one.

If change is required, MITRE should push for it and then help to broker the implications fairly. The Corporation should be prepared in such instances to defend its recommendations against those who will want to take no action until it is almost too late, and when the consequences of earlier inaction will be severe on all those who remain. MITRE must take the long view but push for early action. Most of all, the Corporation must have a good appreciation for what the key players in government can tolerate. There is no sense asking people to do something they cannot, and no sense in antagonizing important people without helping the program. MITRE must stand up and be counted even when key people may not like it, but should do so with full knowledge and with the belief that it is important to the capability and within the wherewithal of the people and organizations involved. MITRE staff must act with the dignity and skill expected of professionals.

But how does the Corporation achieve the necessary understanding of the government's operational needs and capabilities? As mentioned, MITRE's 35 years of work on strategic, tactical, and intelligence systems have provided the staff with a firsthand experience with the various hardware and software systems that are part of the various DOD mission capabilities. The Corporation has had staff working at NORAD, Tactical Air Command Headquarters, Strategic Air Command, Air Force Logistics Command, NATO, and many other operating locations. The work has helped these organizations achieve current capabilities. The experience gained is invaluable to MITRE in systems engineering for ESC of the next-generation C^3I systems. Through other parts of the work program, MITRE staff is familiar with the evolution of potential enemy systems to threaten or defeat U.S. C^3I systems. The staff is also cognizant of enemy C^3I systems in each mission area. MITRE project personnel use the Corporation's unique across-the-board knowledge of the mission area to help advise the U.S. on appropriate countermeasures. Because of

this collective experience, no other organization can even begin to match the breadth and depth of MITRE's knowledge—in the operational missions, in the associated C^3I systems, and in the hardware and software that go to make up these systems. It is an invaluable resource, an unmatched Air Force/DOD corporate memory that is both unique and impossible to replicate. This corporate memory is supplemented in other ways.

On most programs, MITRE participates in the initial planning for the capability and remains on the program as systems engineer through the development phases, testing, and field operation. Having to make a capability function well in an operational situation is both a sobering and instructive experience for the MITRE staff. One learns what is really important, what works, and what does not. The uniqueness of such experience is commented on by A.D. Hall:

> *It is true that only rarely will a particular person, or group, or even a whole organization, follow a system from inception through development, use and obsolescence.*[52]

In MITRE, corporate cradle-to-grave association with a program is more the rule than the exception. It is also true that most C^3I systems evolve in major ways, and the MITRE staff has had the advantage of working on the programs that provide for additions and modifications. As an example, the E-3A AWACS for which the Corporation had systems engineering responsibility has gone through a series of major upgrades to the system capability. In addition, versions of the AWACS have been sold to NATO and to Saudi Arabia. MITRE has had systems engineering responsibility on all the upgrades and on all the foreign sales programs. The continuity of the MITRE work program ensures that the staff knowledge stays current as changes and additions are made. In turn, this avoids any lag in getting up to speed in preparation for the next program.

In addition to DOD programs, MITRE talent has also been applied to many other related government programs, such as civil air traffic

Because of this collective experience, no other organization can even begin to match the breadth and depth of MITRE's knowledge—in the operational missions, in the associated C^3I systems, and in the hardware and software that go to make up these systems.

[52] A.D. Hall, *A Methodology for Systems Engineering* (Princeton, New Jersey: D. Van Nostrand Company, Inc., 1962), p. 11.

control. The Corporation has built up a large reservoir of talented staff with firsthand experience in almost all the DOD's mission areas, as well as in other related areas.

But how do individual staff members achieve this knowledge, understanding, and in-depth appreciation? Like so many other skills that take practice to perfect, the only good way to become a truly outstanding systems engineer is to work as one. Skills in one or more technical areas are necessary, and a devotion to achieving a capability for the customer is essential. One way to become expert at the capability that is to be achieved is to work with it from day to day. MITRE has many opportunities for staff to work at user locations such as Colorado Springs, Omaha, and Langley. There one may see each day what the command personnel do, how they work, what is important, and what limitations exist. Doing that for a generation or more of user personnel begins to help distinguish what is really important and essential for the successful operation of the mission capability. There is nothing like firsthand observation, and if possible, firsthand operation, for the education of MITRE staff on the needed operational capability.

Alternatively, MITRE personnel get many opportunities to visit operating locations to observe existing systems in operation and to discuss their strengths and weaknesses with operating personnel. No other corporation gets this opportunity to the same degree and in so many related areas. This experience is less a teacher than working at an operating location for an extended period, but it is nonetheless valuable.

Short of that firsthand experience at an operating location, many MITRE projects provide a test facility for the evaluation of existing or planned capabilities. In them, MITRE staff can get actual, firsthand experience at trying to make the systems work. Such facilities are not constructed for the operational education of the staff; they are designed to answer specific questions about the planned capabilities. The more realistically they replicate the capability, the greater their utility. Whenever possible, they should be staffed with people

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who know the existing capability and appreciate what is desired in the new one, especially people from the operating commands. However, nothing is better for the education of the staff both on what is needed and what may be possible, on what is difficult to do, and how to do what needs to be done.

Another form of the testbed is the use of simulation facilities. Again, one can learn a lot, but one can also be deluded. The realism of the simulation is critical; the assumptions inherent in the simulation and their validity must be understood. One must be very careful in interpreting the results of a simulation in circumstances where the inputs to the simulation only approximate those of the live system, or when the simulated activities did not include the influence of human operators. Again, when used under the tutelage of experienced people, simulation tools can answer many program questions and at the same time contribute significantly to the growth of the less experienced staff.

Although not directly related to this discussion of how MITRE staff go about becoming knowledgeable about the capabilities that they are trying to help acquire, it is important to comment on the use of such facilities at MITRE. There is nothing about becoming a MITRE staff

member that automatically confers technical omniscience on a person. Some of the programs on which MITRE has systems engineering responsibility are attempting to achieve very new and very challenging capabilities. Doing so often requires facilities where measurements can be made, device performance evaluated, or human interactions assessed. Testbeds and simulation facilities should result only when one is able to pose the questions that cannot otherwise be answered, and should cease to exist when all relevant questions have been resolved. In use, they may help educate MITRE staff. However, their justification must be based on specific program needs, and their existence discussed with and supported by the system program director. The use of such facilities by MITRE for design verification is discussed later in this chapter.

One can learn much from talking to knowledgeable people; however, a person's organizational affiliation does not automatically make that person knowledgeable. MITRE staff who have worked on tactical air control systems for the last 30 years know a great deal about command and control of tactical air forces, as well as about systems engineering. A person newly assigned to a tactical air unit may or may not know the essentials of that mission area. Other potentially good sources of personal contact include the people working on the government side in the SPOs. Many of them have had experience operating in the field or in acquiring earlier systems for the operating commands. Their knowledge and wisdom can be very helpful to MITRE personnel.

As one gets more experienced, one develops a better personal sense of what is important and an improved ability to recognize someone who knows what they are talking about from someone who does not. Not everything one will hear will turn out to be correct. Until one has sufficient experience to distinguish truth from fiction, or important from less so, one must depend on the more experienced MITRE personnel for guidance and support.

Another way in which MITRE staff members may obtain a deeper appreciation for the operational capability that may be required is to attend one or more of the schools that the government has and may

permit MITRE staff to attend. For example, many MITRE people have attended the Air Force Air Ground Operations School in Florida. These schools are designed to educate the military personnel who will be assigned to operate and maintain the capability in question. They provide much useful background for the MITRE systems engineer.

Acquisition programs always include a variety of test phases. There are in-plant contractor tests designed to show that the contractor has produced what was promised; tests at operating locations to show that the delivered system meets its operational requirements; and tests of the new system, along with other existing systems, to evaluate the level of overall capability that has been achieved. MITRE personnel often get an opportunity to witness or participate in such tests. A MITRE staff member will gain precious knowledge by doing so. The depth of such knowledge cannot be achieved in any other way. Following the system you have been working on into the field to see how it really operates is sometimes sobering, sometimes exhilarating, but always educational. Those staff who do it become much stronger system engineers, much more able to take on the next challenge with wisdom and knowledge. From the very beginning, MITRE's staff has gone where the action is. It is part of what makes MITRE people special.

From the very beginning of MITRE, its staff has gone where the action is. It is part of what makes MITRE people special.

The beginning of this section asserts that the uniqueness of The MITRE Corporation as a source of systems engineering on Air Force C^3I systems derived from the corporate form, a deep appreciation of the operational capabilities involved, and over 35 years of experience working as systems engineer on these systems. These points have been expanded on here. It is also noted that the highly qualified technical staff at MITRE and the dedication of the staff and the management to achieving required system capabilities, round out MITRE's unique qualifications as systems engineer for the Air Force's most challenging C^3I systems.

Dealing with Sensitive Systems Engineering Issues

Over time, certain areas of MITRE's work have proved to be especially challenging. Part of the challenge has resulted from the

sensitivity or contentiousness that may surround the Corporation's involvement in these areas. This section describes MITRE's approach to a few of the important but potentially sensitive areas of systems engineering.

Advocating System Capabilities Over the last 35 years, there have been many different attitudes and regulations about the roles and responsibilities of the user commands and the development agencies involved in achieving the required system capabilities. Jousting about who is responsible for what and who is best equipped to do what continues even today. One area that has often come under scrutiny is the role of development personnel in advocating a system capability. At times, the prevailing government acquisition approach has directed that the development community refrain from any form of system advocacy.

In Chapter 2, an approach to system requirements is espoused in which the user community establishes the desired operational objectives. It is further suggested that the user community might establish requirements at the level of operational tasks, but that requirements for specific systems and hardware to perform those operational tasks are the business of the development community. Clearly, such an approach involves both the using and developing communities in the requirements business. There is much room for overlap and for debates about who is responsible for what.

MITRE fully understands and supports the approach in which the user commands—in conjunction with the service headquarters, the DOD, and ultimately, Congress, which provides the resources—establish the system requirements at the level of operational objectives and tasks. The development commands, and others like MITRE who work with those commands, have key roles in describing what is possible, and how much alternative systems might cost. MITRE participates in this work. When an approach is chosen, the Corporation prepares the system specification enumerating the technical requirements that must be satisfied by industry in building the system. In these latter two areas, MITRE contributes to the government's establishment of system requirements.

MITRE recognizes a responsibility to avoid a "requirements creep" or a "goldplating" of requirements that could be introduced, for example, by the specifications it prepares. Every effort is made to meet the stated system requirements without embellishing them. This subject area has historically been one of great debate, especially when an acquisition program has difficulty in meeting the requirements of the system specification. The people in the debate are often not the ones who approved the specification at the time it was written and may have different opinions about what really should have been required.

Despite risks of this sort, MITRE is dedicated to achieving the required system capability as described in the user requirements. In its day-to-day work, the Corporation is a strong advocate of the capability and is always asking what needs to be done to provide it. As noted above, the primary criterion that drives MITRE in its day-to-day work is, "What is the best thing to do to achieve the required capability?" However, if in the course of the acquisition program circumstances become such that there is significant risk that no capability will be achieved, the Corporation may recommend a change in the requirements to preserve essential portions of the desired capability. The Corporation has extensive experience with the capabilities under acquisition through its work on earlier versions of the system or on like systems for other user commands. The nation has paid to establish this knowledge, and it would be wasteful not to apply it. MITRE believes it must advocate the capability in this sense and that it can do so without usurping the responsibilities of the user organizations.

In its day-to-day work, the Corporation is a strong advocate of the capability and is always asking what needs to be done to provide it.

Maintaining System Design Integrity There is one function that clearly belongs to the system engineer and concerns the maintenance of the integrity of the system design as the system proceeds from initial design, through development, test, and field operation. One should be able to relate the technical requirements of the system specification to the documented using command operational needs. This ensures that the stated needs are reflected in the technical specification. It also helps to avoid including extraneous technical requirements that could

be costly and time-consuming. The MITRE-prepared system specification is used by the government in the process of contractor selection.

Later in an acquisition program, traceability to the MITRE system specification should be a criterion for evaluating the contractor specification. A similar chain of logic is followed by the Corporation in assessing other documentation, such as proposed test plans. The question is always of a similar form: "Is what is contained here consistent with the system design? Will the test verify consistency with the system design?" In that way, MITRE is in effect asking, "Will this contribute to achieving the required capability?"

The system specification acts as a standard to be used by the Corporation in evaluating events that take place on the program. As has been discussed, dynamic change is a way of life on a major acquisition program. As other events occur, both within the program itself and in other related programs, MITRE evaluates them for impact on the system design. Changes in requirements may affect system design. Similarly, changes in areas such as technology or threat, or development breakthroughs or failures, may require system design changes. In any case, MITRE as part of its evaluation of the current situation is always examining the impact on the system design. Retaining the existing design may be the best thing to do to achieve a capability. The Corporation must be prepared to recommend that and to identify any actions required to do so. Alternatively, circumstances may be such that MITRE will recommend that the system design be modified to obtain the operational capability. Again, the impact of doing so must be described. MITRE must be pragmatic in its efforts and know when compromise is necessary. At the same time, MITRE must be prepared to recommend what is necessary to preserve the design and thereby ensure the capability.

The MITRE staff has extensive educational backgrounds that help provide a foundation for the technical requirements written in a system specification. The staff is similarly steeped in operational considerations through the Corporation's work on large military systems over the last 35 years. With the wisdom gained from experi-

ence and current knowledge of available technology, staff members are well prepared to write specifications for new system capabilities that may be required by the user community. However, this does not mean that in every case the staff can do so without investigating some of the potential unknowns or without evaluating areas of high risk. It is further true that such investigations and evaluations are often in very complex technical and operational areas and are not amenable to mere pencil and paper analysis.

Performing Design Verification Historically, MITRE's work to resolve unknowns or evaluate risks on an acquisition program has been referred to as design verification. Design verification may start very early in the process, even before the overall system design is complete. It continues throughout the program. As noted in a MITRE paper, its objectives may include establishing a workable design, choosing among competitive designs, optimization of a particular design, or early identification of unforeseen problems.[53] The methods of design verification may include one or more of the following: theoretical studies, modeling, simulation, mockups, engineering models, and prototypes. It should be pointed out that the MITRE corporate memory carries over from program to program and helps to minimize the need for design verification.

MITRE's design verification activities provide information to all program participants, not just the Corporation. Even simple efforts such as model shop versions of operator consoles, or prototyping of electronic displays, are very helpful in assisting user personnel to visualize the operator facilities. This visualization provides a good basis for user personnel comments on the planned system design. The early understanding of what is involved may also help the user command in planning for personnel staffing and training.

At the opposite end of the spectrum, if the government is assessing how to best spend its limited resources to improve air defense in some operating area of the world, the MITRE answer may require

[53] J.W. Shay, *MITRE System Engineering Book Outline*, W-07353/0000/01, The MITRE Corporation, Bedford, MA, December 1964.

considerable study and simulation. Such studies would assess the current capability and the contribution that might be made to it by alternatives, such as a major new radar system, or expenditures for higher capacity or more survivable command and control centers, or the acquisition of a new and more capable weapons system. Government decision makers, in turn, can also use the analysis data that would not be otherwise available to choose among the possible alternatives. Such a study could not be done by profit-making industry without potential for conflict of interest, and there are no alternative sources with MITRE's long and deep experience in areas such as air defense and other military mission areas of which C^3I systems are such an integral part.

Design verification requires facilities and personnel resources. No one should expect MITRE staff to have all the answers without investments of the sort common to all professionals.

Design verification requires facilities and personnel resources. No one should expect MITRE staff to have all the answers without investments of the sort common to all professionals. One would not think of pursuing a new airplane program without many different analyses and wind tunnel tests. Similarly, resolving some of the unknowns, or evaluating some of the risks on challenging C^3I acquisition programs, also require design verification activities. The Corporation must identify areas that clearly require MITRE system design verification work and vigilantly pursue the resources necessary to do it. Alternatively, special studies that are best accomplished by other program participants should be recommended by MITRE and pursued until they are successfully accomplished.

What is important here are the questions to be answered, the unknowns to be explored, the risks to be assessed and reduced, as they affect the system program for which MITRE has the system engineering role. Too often, one tends to talk about the facilities and personnel required to do the work and not enough about the questions to be answered and their importance to a successful acquisition program. This latter approach may inadvertently create tension between MITRE and the SPO and rejection of the MITRE initiative, as though the proposed effort had no bearing on the acquisition program.

Clearly, a program director has very limited resources and many areas in which to use them. The number of MITRE staff available to support the program is always constrained, and the jobs for them to do are many. It is quite understandable that a program director would hope that MITRE staff knows all the necessary answers without doing special studies and experiments that can consume significant resources. It is equally clear that a program director will want to be sure that an investment in MITRE design verification work is in the best interest of the overall program. The Corporation must be careful in recommending and describing such activities to be sure they are necessary to meet its obligations under the systems engineering role. Similarly, the program director must provide the necessary MITRE staff years of effort and the facilities necessary to perform approved design verification activities. When the questions have been answered and the risks assessed, these facilities and the personnel who use them should be redirected either to other work on that program or to other programs.

Design verification is a crucial systems engineering function, no matter which organization performs in that role.

Design verification activities, matched to the needs of the individual system acquisition program, are an essential ingredient of MITRE's systems engineering work. In discussing the need, the Corporation must be prepared to describe in detail what unknowns need to be resolved, what risks require investigation, and why. Then, an approach to doing so must be proposed. Finally, the resources required must be described. It is only after the need for design verification is agreed upon that discussing the facilities to do so makes any sense. In that way, the connotation that such activities are an unnecessary cost of doing business with MITRE will be eliminated. Design verification is a crucial systems engineering function, no matter which organization performs in that role.

Assessing Program Changes The acquisition programs that provide the systems necessary to achieve important government capabilities are large, complicated, very costly, and take years to complete. Many government agencies and industrial concerns are involved. Each program is conducted in a competition for resources with the other

funding demands placed on the government. The competition for funds continues annually throughout the life of the program, and the competitors are constantly changing. It is not difficult to imagine in such circumstances that the program will be subject to many changes both from within and without.

One of the major functions of MITRE as system engineer for many of these programs is to help the government anticipate the need for change and make those changes deemed necessary at any time in the program. Changes in the planned acquisition program may be necessary to react to a new enemy threat, adapt to new information on the available technology, accommodate modified user requirements, or compensate for failures in some portion of the planned acquisition. Modification of the program may be dictated by things that happen in other related programs that are contributing to the mission capability. Changes in the available money or other resources will often require modifications to an acquisition program. Change management is a critical function of the system program management office. As system engineer, MITRE plays a special role in helping the SPO perform that function.

Often, MITRE will have to make judgments based in part on the professional experience of the staff. The Corporation must be prepared to do so and to strongly recommend appropriate action.

Before discussing MITRE's participation in the change control process on a program, there are two cautionary observations that need to be made. As mentioned so often in this book, the MITRE criteria for evaluating the need for a change or the specifics of any proposed change, are based on what is the best thing to do at this time to achieve the required capability on a reasonable schedule and at a reasonable cost. As discussed below, this evaluation will often have to be done when there is less data than one would like, and when different program participants have strongly varying opinions on how to proceed. Often, MITRE will have to make judgments based on the professional experience of the staff. The Corporation must be prepared to do so and to strongly recommend appropriate action. MITRE's success in a given instance will be determined, in part, by the strength of the relationships the Corporation has built during the program, and particularly by the relationship between the government program director and the MITRE project leader.

The second cautionary note should be a little more obvious. MITRE is not in the business of crying wolf all day, every day. As noted above, the Corporation must be correct in its professional assessments and must also be careful not to bog down the system with trivia. One must distinguish those actions that are truly significant to the achievement of the capability from those that one might refer to as neatness. A faulty design may critically affect the capability, a misspelling in a specification may merely be a problem in neatness. MITRE must carefully distinguish those matters that are critical to achieving the required capability. As a corollary, the Corporation also needs to give credit when credit is due. When one of the program participants has done a good job, MITRE should stand up and say so. If a specification is good for the most part but has a few problems, the Corporation's comments should include recognition of the good, along with description of what needs to be changed. In other words, MITRE needs to be both objective and professional.

It should be noted that the need to make a change can often be viewed in two different ways. Some people will look at the need for change as a problem—more work, or more money, or a sign of failure. Others will look at change as an opportunity—to increase the chances of success, improve the capability that will be delivered, or eliminate some problem that existed. To cite one example, Congress at one time threatened to stop funding the AWACS program. Some members of the Congress felt that since AWACS was intended for continental air defense, and since that threat was no longer significant, the program should be canceled. That certainly created an unanticipated problem for the program and for anyone who believed the AWACS represented an important national capability. However, thoughtful people in MITRE and elsewhere had always viewed AWACS as a system with potential utility in a wide variety of mission areas, not just continental air defense. Many felt AWACS could make a valuable contribution to tactical command and control. To examine that possibility, the Air Force decided to demonstrate the system's capability in Europe. MITRE played a major role in that demonstration, and the flight tests were successful in helping important people to realize the multimission capabilities of AWACS. Funding

NATO Secretary General Luns at AWACS European Demonstration

In every problem, there is opportunity; one has only to find it.

was quickly restored and the capability of the resulting system has been repeatedly demonstrated throughout the world in a variety of operational situations over the last several years.

The decision to provide an early demonstration of AWACS system capability in Europe, for everyone to see, was a challenge. It had not been planned. New effort and resources were necessary, and there was significant risk of failure. However, the Air Force, and especially the system program office at ESC, MITRE, and the system contractor, Boeing Airplane Company, all viewed the European flights as an opportunity to demonstrate what they thought was an important mission capability. More than that, MITRE suggested that early MITRE-built, advanced development data link terminals should be used to distribute the AWACS data in real time from the aircraft to a variety of ground and seaborne installations throughout Europe. In that way, people on the ground could see for themselves what information the AWACS could provide and how it might be distributed to friendly ground command and control facilities. The recommendation was accepted and resulted in the first demonstration of what is now known as JTIDS. MITRE staff participated directly in the successful flight tests. The demonstrations not only helped restore AWACS funding, but through the initiative taken by MITRE, they gave major impetus to the fledging JTIDS program. In every problem, there is opportunity; one has only to find it.

The anticipation and accommodation of the future need for change is one part of MITRE's systems engineering role. In planning for a mission capability, one finds that the capability will evolve over time as new subsystems become available. The command and control facilities will have to process data from new sensors or will have to exchange data with new weapon platforms that place new demands on the control system. Since each of the acquisition programs is being carried out on its own schedule, and since the command and control facilities must interact with all of them, design of the C^3I systems must account for this evolution. Evolutionary development of the command and control facility may be dictated. A plan needs to be developed in which the system is delivered in increments designed to match the systems being provided by other SPOs. To facilitate implementation of the plan, the MITRE-prepared C^3I system specification may require the use of design approaches that facilitate adding system capacity or special features as the need arises. Modular design of the hardware and software, or the use of bus communications for interconnecting the modules, are two such possibilities.

MITRE's anticipation of future needs cannot be limited to system design considerations. Perhaps special equipment will be required to test the new capability, but not to operate it. The Corporation should recognize such a need early in the program and work with the SPO to ensure the test equipment is available to match the test schedule. If not recognized in a timely way, such needs can cause significant delays in the program schedule and may result in major cost increases as the system waits until the necessary test equipment is made available. MITRE staff members need to continually think ahead in all areas to anticipate what needs to be done to increase the probability of achieving the required capability in a timely and cost-effective manner.

Most of the changes that take place over the life of an acquisition program are not specifically predictable. One might foresee that resources for strategic defense will be shrinking over the next 10 years, without being able to foretell whether the cuts will take place

in force structure, development funds, weapons, or command and control capabilities. Such cuts might take place when no reasonable person would have predicted them. Few people foresaw the rapid pace of change in U.S./Soviet relations, and therefore few anticipated the obvious impacts on defense programs. Indeed, most of the changes that must be accommodated in an acquisition program are not ones that can be specifically planned for ahead of time. They often represent difficult choices that must be made in a timely way to minimize their impact on system performance, schedule, and cost.

It is also true that most of the unanticipated change that must take place in a system acquisition program does not stem from global issues such as congressional funding cuts or improved U.S./Soviet relationships. Events such as these are of great significance, but they are few and get everyone's attention. Indeed, most of the need for change is the result of a variety of things that always take place within a given acquisition program or in a related program with which it must interface to provide the required mission capability. A piece of the system will not quite meet its performance requirements and a decision will have to be made either to fix it, or to modify some other part of the system to compensate, or perhaps to live with the reduced capability. An activity will not be completed on time and other activities will potentially be affected. Work-arounds will have to be found to minimize lost time and resources. New people will be assigned to the program in government or industry, and they may have different opinions about some of the details. As noted in Chapter 3, the environment within which these programs are conducted is incredibly complicated. Managing change is one of the most challenging tasks facing the government program director. As systems engineer, one of MITRE's most important efforts is to help the program director do that in ways that ensure the needed capability is achieved on a reasonable schedule and at a reasonable cost.

To do that, MITRE must be aware of what is happening in the environment within which the program takes place. The Corporation must also understand firsthand the status of all activities on the pro-

gram itself. Staff must study potential risk areas, perform the necessary design verifications, read the associated documents, attend the various tests and analyze the results, participate in program reviews, assess progress, and become familiar with all relevant activities. MITRE must take the initiative to identify opportunities and problems, and to recommend actions to exploit the opportunities or to overcome the problems. The Corporation must prepare alternative courses of action, evaluate them, and provide the information to government decision makers. MITRE staff must be proactive in this regard. However, a well-informed MITRE staff is also prepared to advise the system program director on recommendations made by other program participants. In consonance with the program director, MITRE must work for changes necessary to achieve the required capability, and against those that are unnecessary or detrimental to that objective.

MITRE must take the initiative to identify opportunities and problems, and to recommend actions to exploit the opportunities or to overcome the problems.

In helping to manage change, the staff must recognize that within each large program, immersed as it is in its universe, there are many simultaneous activities that could dictate change at any given time. The challenge is to recognize those that are important and deal with them swiftly. Every day there will be more happening on a program than can possibly be absorbed and responded to in real time. That problem will face MITRE and the system program director, as well. The Corporation must work to eliminate the trivia from consuming program resources and direct attention to the most important matters, while at the same time helping the program director deal with other necessary activities. Program directors are often required to carry out effort only remotely related to achieving the capability. Briefing visiting dignitaries is one mundane example. Such activities take time and resources away from the program, but they are important because the program director has to see that they are done, and done well. Since MITRE is in the business of helping the program director, the Corporation must be prepared to provide professional support to them. With limited resources, achieving appropriate balance among these demands, while ensuring that MITRE's direct responsibilities are effectively met, is the daily

challenge faced by the MITRE project leader. The quality of the MITRE/program director relationship will be a function of how well the project leader makes the necessary choices. This relationship, in turn, will determine how effective the Corporation is in helping to achieve the required capability.

There is another aspect of the challenge to MITRE in helping to manage change that deserves discussion. Obviously, the timeliness of MITRE's advice is very important. In most cases, the earlier one recognizes the need for a change, the less the change will cost, the more readily it will be accepted by those who must implement it, and the earlier the capability will be achieved. A technical recommendation made early in the contractor design phase may be easily adopted by the contractor. No great investment has been made in the design. No one's professional reputation is on the line, so the not-invented-here syndrome is not likely to be a factor. The same technical recommendation at time of production might be impossible. MITRE must always be looking ahead, trying to discern actions that if taken now will be important later. On the other hand, there are factors that mitigate against being able to make early changes.

There is a natural institutional resistance to significant change at any time, not unlike that found in most individuals. This resistance must be overcome if a timely change is important for achieving the capability.

MITRE is often in a situation where it suspects a serious problem is developing, but is unable to prove it, and no other participant is willing or able to corroborate it. Or perhaps other participants are optimistic about their ability to deal with it. The Corporation's professional experience indicates that the problem is real, but the evidence is circumstantial. Contrary to what was said above, such problems are very often difficult to resolve as early as would be desirable. For such problems, the earlier one tries to recommend change, the more difficult it is to persuade people to make it. Change often means additional effort or resources—negotiation with other participants, contract changes, more money, etc. There is a natural institutional resistance to significant change at any time, not unlike that found in most individuals. This resistance must be overcome if a timely change is important for achieving the capability. In situations like this, when the matter is truly significant to achieving the capability,

MITRE's relationship with the program director comes into play. If that relationship is as described earlier in this book, then MITRE will most often be successful in convincing the program director of a crucial need for change. This is true even if the change is contentious and the evidence for it less than absolute.

Another alternative for dealing with risk areas or suspected problems is to take some form of insurance against the occurrence of a later problem. MITRE should consider this approach in attempting to deal with known or suspected risk areas. When necessary, the staff should take the initiative to identify specific actions that should be taken and work as part of the program team to implement them. Everyone wants to believe that things will go as planned. No one wants to hear bad news. Most especially, people who have to do something that is costly or unpleasant as a result of the bad news like it even less, and they have a tendency not to hear. Telling people what they need to hear is never an easy task, but MITRE is paid to do just that. Sometimes the chances of things working out as planned are sufficiently small that the plan to achieve the required capability on time and within cost is in serious jeopardy. MITRE must be sensitive to such situations and take the initiatives deemed necessary to reduce the risk to an acceptable level. Again, it is human to hope for the best. With limited resources, one tries to avoid using them to hedge against future possible risk. But sometimes professional experience dictates that action is required to avoid serious problems later in the program. Such occasions arise in every profession. To reiterate a point made earlier, MITRE must be prepared to give the program director the benefit of the professional experience of its staff. Again, the Corporation's prior work on the program will heavily influence the program director's response.

As noted above, some changes are readily accepted if made early in the program. A change in the design phase is more readily made than after the first units have been produced. Software changes in the coding phase are much more readily done than after the system becomes

operational. For such matters, as the program progresses in time, it gets increasingly difficult to convince people that a change is required. Resources have been invested in the current approach, commitments have been made to important people, no one likes to admit to being wrong, and in some cases the resources most capable of making the change are no longer available. MITRE must evaluate the need for the change and the manner in which it might be done. The Corporation should then work as part of the program team in getting the necessary changes approved and implemented.

Obviously, making changes is costly and time-consuming. Questions such as who should pay for the change always arise. The answers are often legitimately argumentative. Usually, all the parties involved have contributed to the situation, and all have to share in its resolution. It is always helpful to try to separate the concern for who pays from the nature of the change itself, although that is not easy to do. If such an approach is used by MITRE, what is best for achieving the capability becomes the paramount consideration, rather than who is at fault for the problem and therefore who should pay. When the stakes are high, some parties will evaluate the situation first on the basis of who is liable, and only secondarily on what is best to achieve the capability. The Corporation needs to be prepared to deal with that situation. In other cases, who will have to pay can become more of a factor for everyone. For example, when there are a variety of possible solutions that vary in who will provide them, the evaluation provided by MITRE needs to specifically include this factor.

Judging which changes are absolutely necessary and when they should be made, is a very difficult management task. Helping the SPO to do that is a major MITRE systems engineering effort. Doing it well requires a professional attitude, skill, and experience. It demands a dedication to the required capability, thorough understanding of the status of all program activities at all times, and willingness to say what needs to be said. It also requires a relationship with the program director in which he or she relies on MITRE as a full program partner.

Applying System Acquisition Regulations One of the imposing and vexing challenges faced by MITRE in the systems engineering role, and indeed by all participants in a major DOD acquisition program, is the vast array of government documentation that controls or potentially applies to such procurements. As was observed earlier, no regulation can substitute for knowledgeable management in ensuring a successful program. However, some regulations are legally binding on the acquisition process, and some provide good guidance if appropriately employed. Many permit selective application, as may be necessary in any particular acquisition program. The imposition of some regulations may help or hinder the success of a program. Many government agencies are involved in deciding which regulations apply and how. As systems engineer, MITRE is also involved in the proper application of some of this documentation. The overlap between MITRE and government people can be a positive influence on the program when the expertise and experience of the two groups are applied cooperatively. It may also be an area of serious contention when one group or the other is unwilling or unable to take an approach in which the regulations are used to assist the program, rather than unnecessarily burden it with requirements just to be on the safe side. Unnecessary requirements—especially in areas such as testing and documentation—can be an extremely expensive and frustrating process in time and resources for both the government and industry.

Unnecessary requirements—especially in areas such as testing and documentation—can be an extremely expensive and frustrating process in time and resources for both the government and industry.

In-depth discussion of the government's system acquisition regulations is beyond the purpose of this paper. However, their scope will be briefly described here. Some suggestions will be provided on how MITRE should participate in tailoring the required regulations to specific acquisition programs.

Some of the high level documents that have governed DOD acquisition programs for some time include:

- Office of Management and Budget Circular A-109, *Major Systems Acquisitions*, April 5, 1976
- The Federal Acquisition Regulation (FAR) Series
- Defense Federal Acquisition Regulation Supplements

More recently, a formidable series of legislative constraints (Title 10, United States Code) has been imposed. The sections of this code cover subjects such as competitive prototyping, operational testing and evaluation, low-rate initial production of new systems, and the use of competitive alternative sources on major programs. This legislation has led to a revision (23 February 1991) of DOD's system acquisition regulations as found in:

- DOD Directive 5000.1, *Defense Acquisition*
- DOD Instructions 5000.2, *Defense Acquisition Management Policies and Procedures*
- DOD Manual 5000.2-M, *Defense Acquisition Management Documentation and Reports*

These documents describe DOD's approach to implementing the U.S. Code and FAR mandates. They detail the DOD's three major decision-making management support systems: the Requirements Generation System; the Acquisition Management System; and the Planning, Programming, and Budgeting System. They describe the typical program as it passes through concept exploration, definition and approval, and the various phases and milestones associated with system development and operation.

The DOD documentation is supplemented by Air Force, AFMC, and ESC regulations, as well as other related documentation. The ESC regulations emphasize the procedures to be used on Air Force programs to implement the government-wide and DOD acquisition policies and regulations. The combined DOD and Air Force acquisition system documentation is extensive, difficult to comprehend, and potentially detrimental to the conduct of a successful program if improperly applied. On the other hand, the legal requirements must be satisfied. Also, the discipline intended by this documentation is necessary for a successful program. The problem, of course, is to meet the legal requirements and at the same time to provide the needed system capability in a timely, cost-effective way. MITRE must understand the intent of this documentation. MITRE must also assist the program director in judiciously applying it to the system acquisition program.

The acquisition regulations tend to fall into three general categories. The first, lower level group tends to deal with the physical world. This group is normally referred to as military specifications and standards, or MILSPECS and MIL-Standards for short. For example, radiation hardening requirements may reside in a MILSPEC. The documents in this group are slow to change. A listing of 53 of the more common ones is contained on page 6-A-5 of DOD instruction 5000.2. A second category of acquisition regulations governs the interactions between the SPO and the contractors. Most of these documents tend to change only when affected by the third group. The third category, however, tends to change quite often as a result of congressional and other high-level initiatives regarding acquisition strategies and approaches. As systems engineer, MITRE must concern itself with all three levels of documentation.

Needless to say, requirements dictated by imposing government regulations such as MILSPECS cost money. The contractor's time and resources are spent trying to meet the requirements of the specifications. The government and MITRE must review the contractor's work. To avoid expenditures that do not contribute to achieving the required capability, one must be careful to impose specifications only if they are required. Even when a specification is imposed, MITRE must be prepared to help tailor the specification to the system at hand. At a global level, it makes no sense to apply the same standards to commercial hardware and militarized equipment. Will the system be maintained by contractors or by government personnel, and how does that affect documentation and test equipment requirements? Some of the questions may be much more difficult to answer. Should the contractor be required to provide documentation that is suitable for the government to use at a later time to competitively procure additional systems? This reprocurement data, as it is referred to, is very expensive and often not used. How does one decide that the government will never reprocure an item? Perhaps even more difficult, how does one get all parties on the government side to agree to the answer?

In a more technical vein, how much software testing is required to ensure proper system operation? Should a management information system be subject to the same testing as a missile warning system? How secure does the system have to be? How will the system security be demonstrated? Answering questions such as these, and those mentioned above, requires two classes of expertise—one that has an in-depth understanding of the government's regulations, and a second that understands the needs that the government is attempting to satisfy through any given system acquisition program. MITRE has expertise in both areas and a responsibility, as systems engineer, to apply that expertise in advising the program director on the application of government regulations.

The Corporation must work closely with ESC staff groups responsible for areas such as reliability and maintainability, system costing, and procurement. The MITRE project personnel who are counterparts of these groups should strive for consensus on what should be required in a given system acquisition so that the program director is receiving common advice from both MITRE and the ESC staff. At the same time, important differences should be identified and referred to the program director for decision.

The second category of regulations—that governing the contractual interactions between the government and industry—is also an important area of MITRE effort. The Corporation prepares the technical specification that the contractor must satisfy, and participates in the preparation of the SOW and the CDRL. The SOW may have requirements on systems engineering, software development, and various kinds of system and subsystem testing. The CDRL establishes the data that the contractor will provide and that must be reviewed and either accepted or rejected by the government. All of these areas impinge on the achievement of the needed capability, and therefore are of concern to MITRE as systems engineer. Other areas in this category that are of concern include packaging and marking, inspection and acceptance, schedules, government-furnished support resources, security classifications, and the award fee plan if one is to be used.

The third general category of government regulations concerns general system acquisition management strategies. They tend to change as weaknesses in an existing approach in specific cases are recognized and alternatives to overcome those weaknesses are mandated by high levels of government. Unfortunately, there is no universally applicable "right way" to manage an acquisition program. Each program is different; each approach is more applicable in some circumstances, less so in others. Building a prototype is sensible when one is not sure of a technical approach, a waste of time and money when one knows what is to be done and how to do it. Buying something that is substantially unknown through a fixed price procurement is almost guaranteed to produce something different from what was planned, or require more time and money. Therefore, "fly before buy" or "everything fixed price" are unreasonable if they are mandated on every acquisition program.

Unfortunately, there is no universally applicable "right way" to manage an acquisition program. Each program is different; each approach is more applicable in some circumstances, less so in others.

Regulations at this level tend to be cyclical in nature, driven first by the experience of the government's most recent acquisition programs, and second by the knowledge and opinions of people who change quite frequently at this level of government. This cyclical nature is well illustrated by the repeated changes in the government's position on whether systems should be procured on a fixed price or cost basis. When one approach does not seem to work, another is required, sometimes returning to one used in the distant past.

MITRE must fully understand the regulations in this category as they exist at any given time. The Corporation must also appreciate the potential pitfalls that are built into any particular approach. This is another area where the Corporation's long experience in systems engineering on large ESC systems is helpful. Having lived through earlier programs, MITRE has a greater appreciation for the limitations of a given acquisition approach than some others may have. The Corporation should identify the problems that exist in applying a given acquisition approach to a new program. Even if the approach is still required, MITRE should help the program director initiate additional activities to minimize the impact of those problems. Perhaps

the contractor may be asked to perform additional tasks as insurance against a potential problem, or perhaps MITRE, the government, or another contractor may do so.

MITRE's role is to help the government achieve a needed capability on a timely basis and at a reasonable cost. The Corporation needs to recognize at any given time what specific action would best achieve that end. Understanding what needs to be done, MITRE must relate that action to the regulations that govern the procurement. The question to be answered is, "How can this specific action be taken while satisfying the requirements of the existing regulations?" Interestingly, one finds that the existing regulations are really quite permissive. The Corporation needs to work closely with the program director and the ESC staff responsible for these areas to achieve agreement both on what is necessary and how it can be accomplished within the framework of the government's regulations. The approach requires identifying what must be done first, then figuring out how it can be accomplished. It is too easy for someone to say, "You can't do that because the regulations forbid it." It takes considerably more insight to know what must be done, and how it can be accomplished while meeting the letter of the law. MITRE must be familiar with the regulations to help get done what needs to be accomplished to achieve the needed capability.

The existing procurement regulations are really quite permissive.

Four Horsemen of C³CM

Special System Considerations

A theme of this book is that the MITRE approach to systems engineering of C³I systems is based on two important qualities found in its professional staff: a thorough, in-depth appreciation for and understanding of the operational mission capabilities in which the C³I systems play an important part; and skill in all the relevant technologies. However, systems engineering at MITRE involves a series of professional disciplines that are not limited to operational and technical considerations. Some of these important disciplines are discussed in this chapter.

The subjects discussed below tend to fall into two general categories. The first category is driven by factors external to the program. Some of them are important aspects of the environment in which the system is being developed. They are first-order concerns in both the initial system design and in subsequent systems engineering activities. They are not static or one-time challenges. For example, the threat can change quickly and dramatically, as recent world events have so clearly emphasized. To be effective in these areas, MITRE staff must remain current on the environment in which the acquisition is taking place, as well as the one in which the system will eventually operate.

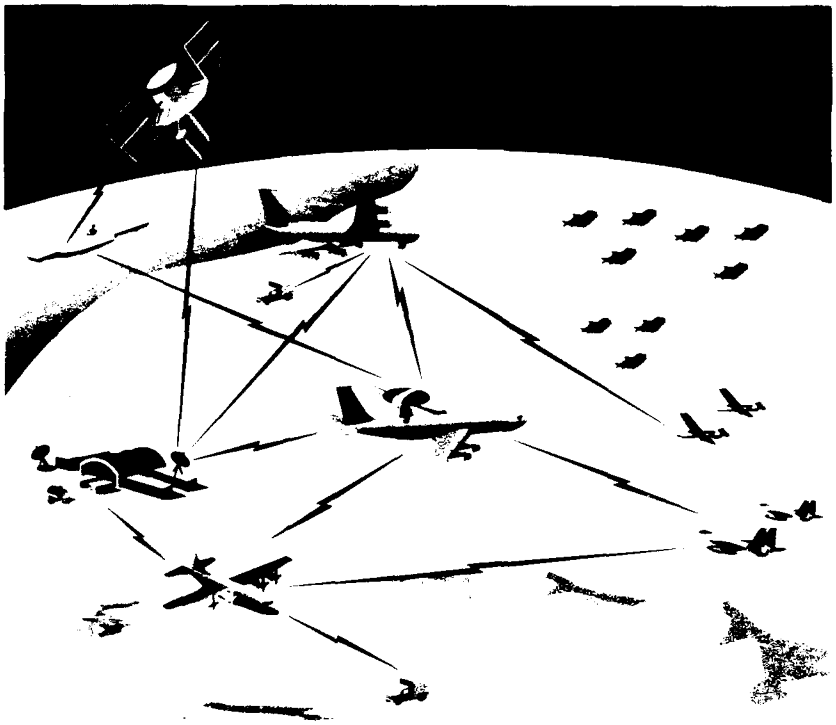
The other class of subjects discussed in this chapter are internal system design factors that cut across the individual functions of a C^3I system. Experience dictates they can cause serious system performance problems if taken for granted in the system development process. These include functions such as system performance monitoring and system exercising. Clearly, the operating command must be able to determine whether the system is performing as required and must be able to train personnel in its operation. System considerations such as these apply to all the C^3I functions ranging from surveillance to information processing and communication of results to other portions of the mission capability.

To be effective, the MITRE systems engineering team must include staff with expertise in the areas described below. Their work must be an integral part of the Corporation's systems engineering activities.

Interoperability

As discussed earlier in this book, the DOD acquisition process provides individual pieces of an operational mission capability, such as air defense. These pieces, or subsystems, are then combined by the user command to achieve the required capability. Each of these subsystems—a radar, communication equipment, command center, or weapon platform—is often referred to as a system. One sees and hears references to the F-15 weapons system or the Milstar communications system. As we have seen, some years ago a term was invented to provide a label for the collection of such systems that constitute the overall mission capability, i.e., the system-of-systems. An interesting discussion of the management challenge represented by "supersystems," as they are sometimes called, may be found in a MITRE document written by Dr. N. Waks.[54] This reference points out that the term used to refer to such systems has been modernized to "macrosystems" when referring to programs of the scope of the Strategic Defense Initiative. In this book, the term "capability" is

[54] N. Waks, *The Management of Very Large Technical Systems*, M89-77, The MITRE Corporation, Bedford, MA, January 1990.



Desert Storm Interoperability

used rather than "system-of-systems" and includes the amalgamation of many systems. It provides the operational emphasis so important to communicating the ultimate aim of systems engineering: mission system capability.

The need for the many subsystems and systems that constitute the total mission capability to effectively interoperate with one another represents another major systems engineering challenge. Each of the items is acquired by a different government program office; each may be built by a different corporation; the schedules for the pieces are time-disparate; and there is no requirement to coordinate changes in one piece with the interfacing pieces before making the changes. Once acquired, each piece evolves on its own schedule, sometimes without the involvement of the development community. Evolutionary, incremental improvements provided by the development community need to accommodate such changes as they are made by the user command or by the AFMC. There is, indeed, a major management and technical challenge to be overcome in achieving the required system-of-systems capability.

MITRE has had, and continues to have, systems engineering responsibility for many of the C³I subsystems that partially constitute operational capabilities, such as strategic defense or tactical air operations. C³I systems are the glue that ties the pieces of the capability together. They provide the facilities for user command management of the operational capability. Because of MITRE's systems engineering responsibility on so many of the C³I subsystems, and because of the Corporation's dedication to helping the government achieve required capabilities, MITRE's systems engineering staff gives special emphasis to the interoperability among not only the C³I subsystems, but also between the C³I systems and other portions of the capability, such as the weapons systems. Interoperability is an important consideration in all of MITRE's systems engineering work.

It should be noted that the challenge of interoperability becomes greater and greater as joint operations involving all the U.S. military services evolve in scope. New technology has accelerated the pace at which operations may be conducted, and has permitted significant increases in the demand for precise control. Both of these facts complicate the interoperability problem. Again, MITRE is uniquely positioned to help. These requirements put a major burden on the C³I systems—MITRE's forte. The Corporation has the background that comes from working on systems employed by all the U.S. military services and on many of those used by allied nations. That experience, combined with the Corporation's dedication to helping the government achieve required mission capabilities, provides a unique opportunity and responsibility for it to help with the interoperability among the systems that constitute the capability.

Clearly, two systems that are physically interconnected must provide for compatible electrical characteristics on each end of the communications lines that connect them. Ensuring that would seem like a fairly straightforward problem. It is not. One must remember that each of the systems is being developed independently, and that each has its own constraints in time and money. Each acquisition agency has its own approach to minimizing the impact on the program,

especially if the agency is committed to an approach and the developers of a new system wish to accomplish the interface in a different way. Even the relatively simple interface problem of electrical characteristics gets more complicated when one includes international systems. In one case, MITRE was asked to help achieve an interface between two national systems in Europe. Neither country wanted to pay for it, and it was not always clear that both really wanted the interface to work!

But achieving an effective interface is more than compatible electrical characteristics. Each of the systems has to speak the same "language." If two systems are to exchange information on aircraft being tracked, each must be able to accept the message from the other, extract the information on track position, velocity, identification, and altitude, and store the result in its own track storage tables. When one system identifies an aircraft as a "faker," the other must understand the meaning of that classification. One must be concerned about converting from the coordinate system of one system to that of the other. Life gets even more complicated when one considers operations in which the control facilities of one service or one nation will be employed with the weapon systems of another.

To the extent possible, in carrying out its systems engineering work, MITRE must anticipate interoperability problems and incorporate the resolution into the system technical requirements. The Corporation also must be prepared to help negotiate changes to existing systems necessary to accomplish the required interfaces. There is another alternative for creating the interface that seeks to avoid modifying the systems that must interoperate. This involves creation of a separate interface system that takes information from one system, translates it into information that can be understood by other systems, and then forwards it to those systems. The translator also processes data in the reverse direction. Such an approach has been used when, after two or more systems have been built, a requirement is established for them to interoperate. Changing the existing systems can be a very time-consuming and costly process. It may take a very

long time to achieve agreement on who will do what to which systems, to decide who pays for what, to establish contracts to do so with the appropriate industrial corporations, and to carry them out.

The compromise alternative is another system to achieve the interface. Again, MITRE has considerable direct experience with such devices for each of the U.S. military services, and between U.S. systems and those of allied nations. For example, MITRE built prototype units that provided an early interface between the Air Force 407L Tactical Air Control System and the NATO NADGE air defense system. These prototypes were eventually replaced by commercial units. The interface has been operationally effective and the approach adopted was more practical than trying to change both of the interfacing systems in significant ways. However, the extra system has to continue to be supported by the user commands and upgraded as the interfacing systems are modified in ways that affect the interface.

A very important part of MITRE's systems engineering activities is attention to the interoperability among the various systems that constitute the mission capability. This work is demanding, tedious, and never-ending.

All the above discussion is to make one simple but crucial point: A very important part of MITRE's systems engineering activities is attention to the interoperability among the various systems that constitute the mission capability. This work is demanding, tedious, and never-ending. It requires patience, persistence, dedication, in-depth knowledge of the interfacing systems, and most of all, a skill at negotiating with the many players involved.

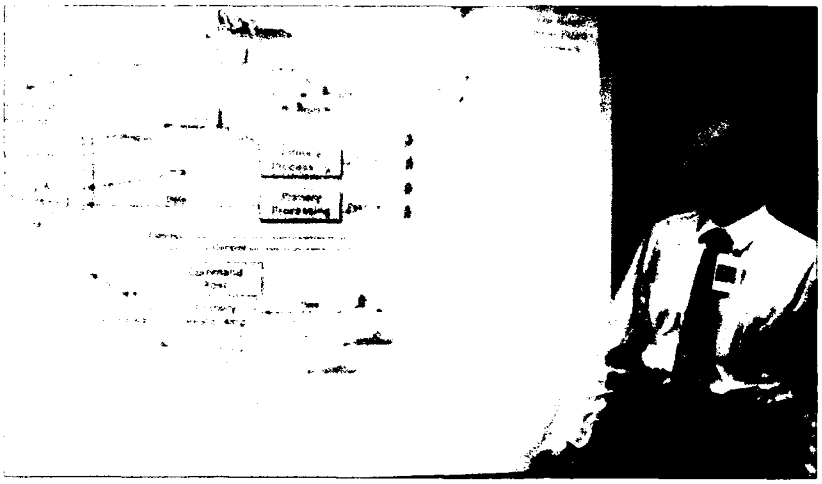
Threat

On any given C^3I acquisition program for which MITRE has system engineering responsibility, its staff members have access to government intelligence information on current and projected capabilities of potential enemies of the United States. This access is necessary to ensure the validity of the system requirements reflected in the MITRE-prepared system specification. As in so many other areas of C^3I systems engineering, it is not enough that some government agency reviews a draft specification and requests changes to reflect the threat. MITRE staff must understand the

threat and must remain current on its evolution. There are simply too many occasions as the C^3I system proceeds day by day, month by month, through source selection, development, testing, and operation, in which this understanding by MITRE can help ensure that decisions are made in the best interest of achieving the capability. In the systems engineering role, the Corporation participates in every important program action. Those agencies that are devoted to gathering intelligence information and assessing potential enemy capabilities are simply not involved in that way. The potential threat is a major driver in determining the capabilities required in friendly systems, and like so many other factors, the threat evolves with time, as does the capability itself. It is therefore crucial that the MITRE staff has access to the latest intelligence estimates of existing and potential enemy capabilities.

Even in these days of rapid prototyping and incremental evolutionary development, it may take many years to achieve a desired level of operational mission capability for C^3I system components. As a result, MITRE must pay special attention to potential future threats. But that is an art itself, and people can become specialists in this area. MITRE has been fortunate since its earliest days to have had projects with agencies involved in the analysis of enemy capabilities. This work has evolved over the years to encompass two kinds of activities. One that developed after the Corporation existed for several years involves helping agencies acquire C^3I systems in a manner similar to the assistance that MITRE provides to the Air Force and other DOD services and agencies.

However, the most interesting activity in this section has existed almost from the very beginning of the Corporation and has been continuous in all the intervening years. For example, intelligence agencies recognized that the Corporation's expertise in air defense was applicable to their task of analyzing the capabilities of potential enemy air defense systems. More specifically, under East Wing, a joint Air Force-MITRE project, MITRE staff members have been analyzing the forces and the systems of the Soviet Union for over 25



East Wing Briefing on Soviet Air Defense

In the end, the explicit and implicit threat assumptions that go into the design of a C^3I system are a complex matter of economics and value judgments on both the friendly and enemy sides.

years. Special emphasis has been placed on Soviet air defense systems. The Corporation's work in analyzing Soviet and other potential enemy systems helps to define the capabilities that must be inherent in U.S. C^3I systems. This work is an important effort in ensuring that such capabilities are matched to the real threat posed by enemy forces. It also keeps MITRE current on the state of the art in C^3I development, and therefore better able to provide the required systems engineering support. In addition, the results of the MITRE analyses are valuable to the Air Force in non-C^3I areas as well. For example, the capabilities required in Air Force weapon systems are in part determined by the expected performance of the C^3I systems of potential enemies.

In addition to work for the Air Force, MITRE has also assisted other government intelligence agencies in acquiring required C^3I systems and performing technical analyses of various classes of intelligence data. When appropriate, this information is applied to MITRE's C^3I systems engineering projects.

Obviously, when assessing the threat and applying the results to the design of C^3I systems, one must avoid underestimating the enemy capability. On the other hand, it is equally important that MITRE staff avoid specifying a C^3I system based on an exaggerated "ten-foot tall" enemy. In assessing potential enemy capabilities, a broad view must be taken. One cannot be driven solely by what might be done

since there is also a pragmatic side to the enemy's ability. The likelihood the enemy will take some action or other, and will be successful in doing so, involves the overall demands he must satisfy, his technical capabilities, manufacturing skills, etc. The enemy's estimate of the value of the friendly system and his cost to do something to counter it, are other important factors. In the end, the explicit and implicit threat assumptions that go into the design of a C^3I system are a complex matter of economics and value judgments on both the friendly and enemy sides. Decisions by one side or the other can affect a C^3I system. MITRE must remain current on such factors throughout the life of an acquisition program and work with the government program director to reflect them appropriately into the C^3I system.

It is perfectly possible to conjure up an enemy capability that—if it existed—would negate the capability of the C^3I system under consideration, and therefore say that the system should not be built. Carried to an extreme, that logic results in a paralyzed acquisition system.

A system designed to meet an overestimated threat will certainly be unnecessarily expensive and may well encounter serious development problems. Neither result reflects well on the systems engineer. Making decisions on the level of threat to reflect in the system specification is a difficult task. It requires close coordination with the user command, development agencies, and intelligence community. It is fortunate that MITRE has professional staff skilled in that process, with many years of experience in doing it, and cognizant of the latest information through the Corporation's work with the agencies responsible for assessing enemy capabilities. This combination is unique to MITRE and essential to MITRE's effectiveness in the systems engineering role.

There is another potential pitfall to avoid in assessing enemy capabilities as an input to the design of a friendly C^3I system. It is perfectly possible to conjure up an enemy capability that—if it existed—would negate the capability of the C^3I system under consideration, and therefore say that the system should not be built. Carried to an extreme, that logic would result in a paralyzed acquisition system in which no capabilities were acquired because an offsetting threat can always be conceived. Countermeasures that an enemy may take are discussed as a systems engineering consideration in the next

section. However, it is important to note here that there is never a single threat to which a C^3I system must respond. A system such as AWACS must be capable of operating in a wide range of scenarios and circumstances. The fact that one may be able to define threat conditions that might reduce the capability of a planned C^3I system does not mean that the system should not be built. One cannot afford to design for extreme or remote circumstances. Indeed, the system engineer and the other program participants need to consider the range of circumstances under which the system may operate and assess the contribution of the system to the operational mission capabilities under those circumstances. This may indeed lead to a series of changes in the proposed design. However, eventually one has to decide whether the range of circumstances for which the C^3I system makes a significant contribution is representative of the situations in which the system will have to be employed, and whether a system with these capabilities is worth the cost. If so, the system should be acquired.

The fact that one may be able to define threat conditions that might reduce the capability of a planned C^3I system does not mean that the system should not be built.

One must also recognize that the circumstances outside the program can be modified to make the system viable in a wider variety of situations. Again, to use AWACS as an example, physical survivability of the platform in contested air space is of major concern. The user command, however, can decide to allot some of its friendly fighter aircraft to protecting the AWACS from attack by enemy aircraft, thereby extending the circumstances in which AWACS is a survivable C^3I system. This simple example again emphasizes the close and continuous interaction that needs to take place among MITRE, the development agency, and the operational user command to maximize the utility of U.S. C^3I systems.

As systems engineer, MITRE must understand the evolving threat in detail and must be prepared to reflect it in its recommendations as the C^3I system development proceeds. As always, the question that MITRE must continuously answer is, "All things considered, what action should be taken at this time to achieve the required capability on a reasonable schedule and at a reasonable cost?"

Countermeasures and Counter-countermeasures

This section expands one aspect of the threat discussed above. Any time an adversary achieves a capability, or is in the process of developing a new one, friendly forces begin to think about and take action to counter that capability, or to somehow overcome whatever advantage the new system gives the enemy. The enemy acts in a similar way in response to systems built by the United States. An important aspect of C^3I systems engineering is consideration of how the enemy might choose to counteract the system. Are they likely to try to physically destroy the system or render it inoperable by jamming? Perhaps they will choose to try to overwhelm it by introducing false targets or decoys. They might even try to exploit the system to their own advantage by intercepting information as it is processed and communicated by the C^3I system. These potential tactics—destruction, jamming, spoofing, and exploitation—have come to be known as the "Four Horsemen" of C^3 countermeasures (C^3CM). In contemplating potential countermeasures, MITRE staff must remember both the highly sophisticated threats and the very mundane. Creating smoke may be as effective as building decoys, and it is much easier to do.

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In escalating this process, the friendly forces may then begin to define actions they might take to counter the enemy countermeasures, hence the term "counter-countermeasures." Since such considerations are central to the operational viability of a C^3I system, they are important factors in MITRE's C^3I work. Again, the Corporation enjoys the distinct advantage of having a group of experts in these fields who have been working with intelligence agencies in assessing potential enemy capabilities and with U.S. development agencies in defining and acquiring capabilities to overcome potential enemy initiatives of this sort. MITRE's work has made specific contributions to systems designed to defeat potential enemy C^3I systems. C^3CM tactics were employed effectively by U.S. forces in Operation Desert Storm.

This aspect of systems engineering involves a serious contest of point and counterpoint and counter-counterpoint. Again, carried to an extreme, such a process could lead to a failure to take prudent

acquisition actions for fear that the enemy will do something to counter the system being considered. The considerations of what to do are in part the same as those discussed above. One can change the design to actively counter potential enemy countermeasures. For example, communications can be encrypted to avoid enemy intercept and exploitation. Or one could employ another system to negate the enemy countermeasures by physically attacking their facilities, or by jamming them or spoofing them. In all of this, MITRE's systems engineering staff must be especially wary of equivalent actions by the potential enemy, especially those designed to negate or spoof the friendly C^3I systems.

Survivability

Another important aspect of the threat relates to the physical survivability of the C^3I system. Electronic survivability—jamming, exploitation, and spoofing—has already been covered. However, physical and functional survivability despite enemy attack deserve some further discussion. There are several system design approaches that may be considered. An obvious one is redundancy—an approach in which the potentially vulnerable portions of the C^3I system are replicated so that if one is destroyed, another may take over its function. Another is to make the facilities transportable; that is, they can be moved from place to place to make the enemy's targeting problem more difficult. Or they can be made mobile. A mobile system can be moved and can operate while moving. Decoys can be deployed to increase the enemy's targeting problem. Alternatively, one can employ a variety of hardening techniques, such as underground bunkers. Each of these alternatives has its disadvantages; all of them cost money to acquire, as well as to own and operate. Redundant facilities require more operating and maintenance personnel, as well as more support facilities. They also require complex operating arrangements to ensure continuity of operation during and after an attack. Transportable systems have little or no capability while in transit. Packing up, moving, and

setting up again is a complicated process in which things tend to get broken or lost. Mobile systems are expensive to own and operate, especially if they achieve increased physical survivability by operating from airborne platforms.

As in most aspects of systems engineering, there is no "school solution," no single answer that fits all situations. Each case must be carefully studied on its own merits. How critical is it that the capability be continuously available? What can be done to actively protect the C^3I system, as in the case of fighter aircraft protecting AWACS? How can the enemy problem be made more difficult? What are the risks and the costs associated with the possible alternatives?

As a group, the MITRE staff has had firsthand systems engineering responsibility for systems that employ the various alternatives available for addressing the requirement for physical survivability of C^3I systems.

Again, the MITRE staff has wide experience in such assessments. In its early work on survivable air defense systems, the Corporation was system engineer on programs such as the Super Combat Center, which built an underground facility in North Bay, Ontario, Canada, and in the 425L program, which built the underground facilities at NORAD. More recently, the Corporation had similar responsibilities for the new underground operations center at Strategic Air Command (SAC) Headquarters. MITRE was the system engineer on the BUIC system that provided air defense C^3I survivability through redundancy of the control facilities. MITRE and ESC have recently been a part of programs, such as one for SAC in which transportable control facilities were provided. MITRE has had systems engineering responsibility for airborne C^3I systems such as the Advanced Airborne Command Post, AWACS, and the Joint Strategic Target Attack Radar System (Joint STARS). And for more than 25 years, MITRE has had systems engineering responsibility for a series of rapidly deployable C^3I systems for use by the U.S. tactical Air Forces anywhere in the world. As a group, the MITRE staff has had firsthand systems engineering responsibility for systems that employ the various alternatives available for addressing the requirement for physical survivability of C^3I systems. This experience is invaluable in making meaningful recommendations concerning the approach to physical survivability in the design of new C^3I systems.

The anticipated physical threat can also include damage due to radiation effects of nuclear explosions. This area has been of major concern to the MITRE systems engineering staff on projects such as the Advanced Airborne Command Post and the Milstar satellite communications system. The Corporation has laboratories in which relevant measurements can be made. MITRE staff members have also participated in tests at facilities, such as the Air Force trestle facility used to test the Advanced Airborne Command Post aircraft and equipment for radiation hardening.

One observation that should be made in considering design for physical survivability is the necessity for a sensible balance between the various components of the overall capability. An air defense system might consist of sensors, communications, command and control centers, and weapon systems. In considering the survivability of the air defense system, one needs to ensure that there is a healthy balance among these functional areas. A system in which the communications all pass through a small number of nodes is not survivable even if there are many redundant sensors, control centers, and weapons bases. In such a case, the enemy has an obvious weakness to exploit when trying to degrade the system capability. On the other hand, the subsystems of a total system capability such as air defense are not normally acquired concurrently. It may well be prudent to increase the number of control centers the enemy must target even when the communications systems are vulnerable, as long as there is a plan for restoring balance among the major subsystems as time and money permit. MITRE's dedication to achieving the required mission system capability demands that the MITRE staff be knowledgeable on all aspects of system survivability and prepared to recommend actions necessary to achieve it.

Performance Monitoring

Many of the existing C^3I systems are extremely critical to the nation's defense. To appreciate that fact, one need only consider systems such as those used to control the U.S. nuclear strike capability.

These systems are very extensive and very complicated. It almost goes without saying, then, that the user command must be provided with the means to know that its C^3I systems are operating properly. Another key ingredient of MITRE's systems engineering work is to ensure that the using command personnel can monitor the performance of their C^3I systems with high confidence.

One approach is to provide a series of tests that the user can employ to measure whether a system is operating properly. This can mean expensive test tools and complicated procedures. It requires that the test be properly conducted to avoid misleading results. It sometimes requires that while the testing is being accomplished, the system is not available for operational use. All of these aspects are undesirable. But sometimes they cannot be avoided, especially when one is concerned about overall performance of the mission system capability. For example, to determine whether U.S. missile warning systems are operating as planned requires a very elaborate test program. MITRE has helped define, conduct, and analyze such tests. This aspect of performance monitoring is related to system exercising and performance evaluation, as discussed in the next section.

At a lower level of aggregation, one can provide an individual C^3I system with an inherent capability to monitor its own performance and to communicate the results to user personnel. One common approach is the use of built-in test equipment, or BITE. The use of BITE is another important systems engineering consideration. What measurements will convey an accurate, timely, and affordable estimate of current system performance? What are the criteria for deciding when a failure has occurred, versus a degradation? How does one avoid a high incidence of false alarms? This latter problem has been especially vexing and has required a redesign of the BITE in some systems to make it operationally effective. How does one avoid making the BITE so complicated that another system is needed to distinguish operational system failures from BITE failures? To what level does the BITE have to identify the source of the failure? These are some of the key questions that the system engineer must help answer.

Another possibility is to use one system to help monitor the performance of another. For example, in some air defense systems, the aircraft tracking function in the control center processes the data received from several radars. In particular, the tracking function often has data from several radars on a given aircraft. One might design the software in the tracking program to compare the quality of the data received from the several radars and to identify performance problems in one or more of them. If the system communicates those results to operating personnel, they can be addressed and the problems resolved. The use of one system to monitor the performance of another is an important approach but one that is often overlooked. Requirements for such capabilities are rarely found in the program direction because the systems are developed independently. MITRE should keep this idea in mind as it provides systems engineering support to C^{3}I acquisition programs. Again, one must be concerned about avoiding undue complication of the system while providing capabilities that provide high confidence, low false alarm, estimates of system performance.

System Exercising and Performance Evaluation

In the preceding section, there is a brief discussion of the importance of system performance monitoring functions as considerations in MITRE's C^{3}I systems engineering work. Two related system functions are the ability to exercise the system to maintain high operator proficiency, and an ability to evaluate not just whether the system is operating as planned, but also how well it is performing the operational mission for which it was designed.

It is possible, and often desirable, to build into a system a capability to train system operators. For example, the SAGE air defense system had a Training and Battle Simulation (TBS) function internal to the system. One feature of the TBS system permitted intercept directors to be trained without having to fly live aircraft. The computer provided realistic displays that simulated what an intercept director would see in an actual engagement. The intercept director

gave voice radio guidance commands as might be done in a live situation, and a remotely located pilot simulator entered that information into the computer system. In response to those inputs, the computer moved the interceptor track display on the display console, thereby simulating what the operator would see in the live case. This provided on-the-job training that was important to system proficiency and that would have been very costly to achieve using live aircraft. Use of live aircraft would also have introduced unacceptable safety concerns when the intercept directors were in training and not yet fully qualified.

Some systems have an operational mission all day, every day. One example is the U.S. system for air traffic control. Training for such a system is important. It is equally important and much more difficult to achieve for a system that only operates under certain circumstances. For example, a deployable tactical air control system might only be used operationally in a period of tension or crisis in some remote part of the world. Maintaining proficiency is difficult when day-to-day operation is not required.

The very act of operating a system helps maintain operator proficiency. It also helps to identify changes in procedures that would improve system performance. Substitutes for that must be available when there is no requirement for continuous operation. There must be a capability to simulate the conditions under which the system must be able to operate. Providing such a capability can be a formidable system engineering challenge. The National Aeronautics and Space Administration (NASA) efforts to prepare astronauts for space flight help calibrate how challenging this requirement can be. Military C^3I systems are no exception. For example, how does one provide for realistic training and exercise of the U.S. system for strategic warning, or for the deployable tactical air control system?

One way the operating commands approach this problem is by conducting exercises of several kinds ranging from limited tests of functions such as communications, to full-scale field tests under as realistic conditions as can be established. The exercises can range

from the very simple—pick up the phone and see if you can reach the other party—to very elaborate system-wide tests. One might introduce simulated incoming ballistic missile reports into the front-end of the missile warning system and then exercise the remainder of the system, up to the point of deciding how to respond, as if the reports were real. Or one might deploy a tactical air control system to Europe, set it up there, and operate it for some time together with live aircraft flights in practice air defense and air offense missions.

Such exercises have several redeeming features. They improve operator training and proficiency. They work out the kinks in planned operating procedures. More than that, however, they help to identify any shortcomings in system performance that require attention. For that reason, they are especially instructive to both the operating commands and the development community. As stressed early in this book, a key part of MITRE's system engineering portfolio is an in-depth understanding of the operational mission that a system is designed to support. Active participation in system exercising is an excellent method for improving the Corporation's knowledge and understanding of both operational missions and the potential required improvements in system functionality. Early understanding also speeds the process of satisfying new needs when they are established by the using commands.

The challenge to the system engineer is to provide support for operator training, system exercising, and system evaluation. Some portion of that support is best designed into the system itself. Scenario generators may be required. Realistic simulators may be necessary when live inputs are not practical. Some of these functions may require special test equipment. The other important aspect of this problem is to be sure that means are provided to monitor performance. Some can be done on line while the system is in operation. The system itself may record performance data for subsequent analysis. Clearly, testing is only useful if there is feedback in training or in performance information that can be used to evaluate and improve system operation.

Again, MITRE must include considerations of system training, exercise, and evaluation as an integral part of its system engineering activities during system definition, development, and operational phases. Although less glamorous than some of the other system functions, they are no less essential to effective system operation.

Degraded Operation

> As strange as it seems, in many cases, it is difficult to achieve agreement on when a system is operationally useful and when it is not.

At any given time, it is likely that some parts of a complicated C^3I system will not be operational. Failures will occur. Portions of the system may be taken out of service for testing or for modification. Enemy action may destroy or damage some of the subsystems. As strange as it seems, in many cases, it is difficult to achieve agreement on when a system is operationally useful and when it is not. If a control center has five operating positions and two of them are not working, is the system operational? One may know the condition of the system, and different people may have varying opinions on its operational status. Despite that, a challenging system engineering activity is concerned with how best to provide for useful system operation when portions of the system are not available for whatever reason. This concern with degraded operation has two principal components. First, what is the minimum essential level of operation that the user command wishes to have even under conditions of degraded operation? Second, what failure modes will the system have? That is, how will the system continue to operate as certain systems functions fail or degrade?

The first of these questions addresses the user requirements for minimum essential system operation. If system operation cannot take place without communications between point A and point B, then the system design must make provision for that link to be robust. This can be done through redundancy, by employing multiple media, and perhaps through hardening of the facilities. MITRE must study such requirements very carefully and discuss them thoroughly with the user command personnel. They must be

reflected in the system performance specification and their implementation closely monitored throughout the acquisition program.

The second important aspect of degraded system operation involves the definition and accommodation of failure modes within the system operation. If there is a central computer that is essential to operation, perhaps the system should include a collocated, redundant backup computer. It may be that the system itself should automatically monitor the performance of the computer currently controlling the operation and switch to the backup when a failure is detected. Perhaps the switchover should be under operator control. Or, as another alternative, the situation may dictate a completely separate facility located remotely from the first one. Considerations such as these are both very complicated and very important. Achieving a satisfactory capability in this area, without making the system unnecessarily costly or complicated, is a major challenge. Again, to contribute to a sensible solution, MITRE's systems engineering team must understand the operational needs in depth and appreciate what can realistically be done in distributing this function among personnel, hardware, and software.

There can be no reliability unless it is designed into the system from the beginning.

For system exercising, provision must also be made for crew training in the various system modes of degraded operation, and for evaluating system performance in those modes. Degraded modes of operation will not function properly in operational use unless they are practiced regularly.

Reliability, Maintainability, and Availability

Reliability and maintainability are two very important factors in all of MITRE's systems engineering work. The importance of these factors is widely recognized throughout the acquisition community, and many special efforts are undertaken to provide reliable systems at affordable costs. These efforts vary from those intended to provide highly reliable components to the sorts of questions just discussed in the previous section. One of the MITRE technical centers is dedicated to reliability and maintainability. Personnel

from that center are assigned to each major MITRE systems engineering project.

This section is not intended to provide a treatise on the importance of reliability and maintainability or the techniques for achieving it. Here, only a few general observations will be made. First, there can be no reliability unless it is designed into the system from the beginning. Some aspects of that requirement at the system level were discussed in the previous section. Other related remarks were made in the section on performance monitoring. Obviously, a system device will have reliability problems if the components themselves are not reliable. Less obviously, devices will be unreliable if they are crammed into too little space, or if they do not adequately dissipate the heat generated in their operation, or if the circuits are designed so that they operate at the margins of their capabilities. These are important design considerations as MITRE staff members write system specifications and evaluate the specifications, devices, and systems provided by industry. The approach in which all such factors are considered throughout the development process, rather than just afterthoughts, is now referred to as integrated product development.

What really counts is whether the system is available for use when needed.

The second general observation is that what really counts is whether the system is available for use when needed. In some cases, availability is driven by factors outside the boundaries of reliability. For example, reliability is an important factor in the availability of an attack aircraft to make a bombing run. However, the availability of the aircraft to make bombing runs over some sustained period is the ultimate measure of operational utility. In that context, availability is a product of many factors in addition to reliability of the aircraft itself. A major factor is the length of time required between the return of the aircraft from a prior mission until it is ready to go on the next mission—the so-called turnaround time. Required maintenance is a factor, as are fuel and weapon availability. The availability of pilots to make repeated aircraft flights is another key aspect. Indeed, these latter factors may drive system availability.

This does not in any way diminish the importance of reliability and maintainability. It simply means that there are other important systems engineering considerations as well, because the objective is to attain effective operational capability, not just adequate reliability. Some C³I analogs to the aircraft case are discussed in the next section.

Supportability

The supportability of a C³I system is another important consideration to MITRE in the systems engineering role. This term covers a range of factors, and they may vary with the particular system. To help illustrate them, consider an Air Force C³I system that is to support tactical air operations anywhere in the world, with or without the systems of other U.S. services and with or without the systems of friendly allies. This means many different interfaces between systems. It also requires the capability to operate under many different temperature and terrain regimes. But more to the point of this section, it requires the ability to support the system under a wide range of circumstances.

What is required to support the operating and maintenance personnel with housing, food, water, medical treatment, and a long list of other such items? How will the security of the system and its personnel—physical and other—be provided? What about the care and feeding of the system itself, or spare parts and repair facilities? Is the necessary electrical power to be supplied from the local economy, or does it have to be generated by power units that are part of the system? Where will the fuel come from to feed the generators and other equipment? What can be done to reduce the signatures for enemy targeting that are represented by the heat given off by the equipment or the noise of the generators or the air conditioners? How are facilities to be heated or cooled? How will resupply be managed? The length of the resupply line may be critical. Will spares and other items be prepositioned? These and many other

questions like them have to be of concern to MITRE in its systems engineering role on deployable systems. But there are others.

A deployable system requires transport to move it from one place to another. Within an operational theater, tactical systems move frequently. There must be a capability to tear the system down, package it for transport, move it, unpack it, and set it up for operation. This must be done rapidly and with as little requirement as possible for additional hardware and personnel beyond that required for actual operation. One must also provide for protecting the system and its personnel during transit. Supporting such an operation may require previously prepared sites with accommodations for electrical power and fuel.

The movement of a tactical system from its base in the United States to a location in a foreign country, or from one foreign country to another, requires many of the same considerations surrounding in-theater movement. But the demands on the transportation function are substantially increased. The equipment and its support are very extensive, bulky, and heavy. Some things will fit in some transport aircraft, others will not. In the earliest design work, MITRE must be concerned with these sorts of problems so that when the time comes, the available transport will be able to handle the system requirements. The concerns range from ensuring that the size of the system boxes does not exceed that of the available loading doors, to the fraction of the total available transport that will be consumed by moving the system and its personnel to a foreign country.

The examples in this section are intended to make clear that in the systems engineering role, the MITRE technical staff is involved with many aspects of the overall system, and that some of them are far removed from classical hardware and software engineering problems. They are, nonetheless, system problems of direct concern to MITRE. With a goal of helping the government to achieve the required capability, anything that may impinge on that is deserving of the Corporation's close attention.

System Costing

As in the case of the reliability discussion above, this section does not attempt to discuss system cost matters in any detail. MITRE has a technical center that addresses issues of costs and other related matters as it applies to the C^3I systems for which MITRE has systems engineering responsibility.

Almost since the very beginning of MITRE, there has been a group of professional staff dedicated to supporting the systems engineering projects in matters such as costing and scheduling, management support systems, procurement-related matters, and acquisition regulations. Today, personnel from the Cost Center participate in all the major C^3I system projects at MITRE. Their participation starts very early in the process of establishing a new acquisition program. A portion of the information provided by MITRE to the government on what may be done to satisfy a new requirement includes MITRE estimates on the associated costs of such a capability. These estimates are based on what similar devices have cost in the past, what they are apt to cost when they will be purchased, and what the total system cost is likely to be when all the relevant factors are taken into account. This sort of support continues throughout the life of the program as contractors are selected and as requirements for changes and additions are defined. It should also be noted that the expertise of the MITRE Cost Center covers software, as well as hardware. The Cost Center staff works closely with their government counterparts and with MITRE experts in the various technical disciplines.

A few general points are made here. First, in considering a new system, the cost of acquisition is only one factor. There is also a cost of ownership. What will it cost year after year to own and operate the system? That cost is in personnel as well as dollars. How many people with what types of skills will be required to operate and maintain the system? There are even more global questions in this area. If the system requires personnel with skills in the computer field, will the Air Force personnel system be able to supply them when the demands for similar skills in all the other Air Force systems

are taken into account? How will civilian demands affect Air Force availability of the necessary skilled personnel?

Another general observation concerns the need to be able to estimate what a new device will cost. MITRE cost experts maintain a large database on what different devices with a given functionality have cost in the past. For example, they have good data on the cost of many different U.S. aircraft voice radios. They are able to provide the necessary inflation estimates, and they know the impact of documentation and spares costs as a function of acquisition cost of the radios. However, the real challenge comes in providing good cost estimates for radios using new technology and having new functionality. Those estimates are worked out by a combination of MITRE staff that includes people conversant with the new technology, the Cost Center, and those familiar with the desired operational functionality. Again, the capabilities of the combined MITRE team are effective in providing the best possible cost estimates, ones that are certainly better than any that could be provided by any single group of cost, technology, or functional experts operating alone.

The combined MITRE team can provide the best possible cost estimates, ones certainly better than those that could be provided by any single group of cost, technology, or functional experts operating alone.

There are other essential areas in which the MITRE Cost Center has achieved expertise. Installing C^{3}I system capabilities in a modern fighter aircraft is a very challenging and costly process. Because of the potential for interference with other aircraft systems, and because of the limited space, electrical power, and cooling capacity available on these aircraft, such installations are difficult. That is true even when the installation is part of the original fabrication of the aircraft. It is much more difficult when one tries to retrofit something such as a radio and its associated antenna into an existing aircraft. The space, cooling, and power limitations are greater. Quite properly, the Air Force is reluctant to take the aircraft out of service while the installation is being made. In this area, the MITRE Cost Center has accumulated a database on the cost of installing electronic equipment in various types of aircraft. They also have data on power, cooling, and space availability. That information has been important to MITRE's work on systems such as Have Quick, JTIDs, and Joint STARS.

A third area of expertise for the MITRE Cost Center is logistics support. Again, data is available on broad questions, such as how many systems are required to maintain a 24 hour-per-day orbit of airborne surveillance. At the other end of the spectrum, information is available on the variance in the cost of electronic components as a function of the reliability required. In between, they have data to help estimate what spares will be required, and what maintenance and repair facilities will be needed as a function of the complexity of the system and its availability requirements. Likely documentation costs and training costs are two other aspects of the total system cost with which MITRE staff members are familiar.

System Security

This section does not attempt to discuss system security in any detail. MITRE has a technical center that addresses issues of interest in this area as it applies to the C^3I systems for which MITRE has system engineering responsibility. Some relevant references are provided in the Appendix. As described there, MITRE enjoys a position of national leadership in the computer security area. The Corporation has done much of the advanced work on compartmented mode workstations, which can simultaneously process information with different levels of classification. MITRE has also been involved in the application of crypto-security systems to a variety of communications facilities. As mentioned earlier in this chapter, the Corporation is active in related activities, such as countermeasures to enemy attempts to exploit or jam U.S. C^3I systems.

The purpose of this section is to remind the reader that system security is growing dramatically in importance and scope as dependence on C^3I systems escalates, the technology used in C^3I systems evolves, and the enemy capability to exploit such systems becomes more sophisticated. Breaking the security of German communications was an important contribution to the Allied war effort in World War II. Communications today are much more extensive, and have longer range and considerably greater capacity than they did then. Modern

military operations continue to be very dependent on them. Beyond that, the widespread use of computers creates much more planning and status reporting capability, all of which is of limited use unless it is communicated.

Some modern communications architectures raise special problems. Point-to-point communications require protecting the links. Today's local area or long-haul networks have the equivalent of many point-to-point links that are all potentially accessible from any node on the network. This provides an opportunity for someone to try to access information that was not intended for that person.

Again, the MITRE staff expert in the various subjects mentioned above are essential to the Corporation's full-function systems engineering team. Systems engineering involves much more than the latest technologies and system design. MITRE's unique ability to help in the acquisition of C^3I systems derives in large part from a staff expert in all relevant areas.

The material covered in this chapter touches only briefly on a series of systems engineering concerns that do not fall neatly into some of the more conventional technical and operational disciplines. No attempt is made to discuss them in great detail. However, there is considerable MITRE documentation related to several of these subjects, should one wish to learn more about how MITRE approaches them. The Appendix provides some references to that documentation.

General Ronald Yates Visits MITRE-Bedford

Summary

For over 35 years, The MITRE Corporation has had a close, long-term—indeed, a special relationship with the Air Force. The Corporation was formed in 1958 at the request of the Air Force. This request recognized the unique knowledge and experience within the nucleus of systems engineering talent that transferred from MIT's Lincoln Laboratory to the new corporation. The corporate form and rules under which MITRE operates were conceived to permit it to perform a unique function. With Air Force support, that role has been extended to similarly serve other parts of the government.

In cooperation with the government, the Corporation has configured itself to operate in a conflict-free way. As an FFRDC, MITRE operates under a set of rules designed to facilitate its systems engineering responsibility. It is independent, not-for-profit, does not enter bid competitions with industry, does no commercial work, and does not manufacture. It accepts work only after the government and corporate management have agreed the work is appropriate. All parts of MITRE's operation are open to government review. Personnel are appropriately constrained with regard to

personal outside activities. These factors permit the most conflict-free operation possible. Rather than being limitations, they help make it possible for MITRE to be effective in the systems engineering role between government and industry.

MITRE's charter to work "in the public interest" is closely monitored by a prestigious Board of Trustees that examines the appropriateness of each new class of proposed work. The Board also regularly reviews the adequacy of the Corporation's performance in each major work area. Active corporate management involvement on each MITRE project is a key ingredient in the success of its work. Management interaction with their peers in government and industry also improves MITRE's ability to perform in the systems engineering role.

Through the cooperative efforts of government and industry, there are many very capable military systems operational today. Over the last 35 years, MITRE has been privileged to fulfill the role of systems engineer on more than 100 different C^3I systems for the Air Force and other DOD sponsors. A long history of successful performance provides MITRE with detailed knowledge of the associated operational capabilities and needs, proficiency in systems engineering for such systems, and a C^3I-related corporate memory unmatched by any other organization. To complement these skills, there is a vigorous program to maintain a professional technical staff who are current in all of the technologies applicable to C^3I systems. The MITRE Technology Program, professional development training through the MITRE Institute, very selective hiring, staff interaction with peers in academia and industry, and a dedication to providing the tools necessary for the technical work required on system projects are all facets of MITRE's commitment to maintain a high quality technical staff who are skilled in the latest technologies and have appropriate industrial experience. Joint ESC/MITRE application of the criteria found in ESCR 80-1 to each new project ensures a challenging work program. The high quality of the work program also helps to attract and maintain a

skilled professional staff. Analogously, a high quality staff attracts challenging work programs.

The combination of the corporate structure, a highly trained professional staff, in-depth understanding of the military mission areas, long and successful experience in systems engineering of C^3I programs, along with unparalleled corporate memory in these latter two areas, uniquely qualify MITRE to perform in the systems engineering role for the Air Force and other DOD clients. That special relationship established by the Air Force in 1958 has proven to be most efficacious for the development of effective C^3I systems. It provides an opportunity to influence major programs significantly, and MITRE continues to respond well to the responsibility that accompanies that opportunity.

Despite its designation as an FFRDC, MITRE has no guarantee of work from any government organization. There is no line item in any government budget labeled "MITRE." As an FFRDC, MITRE will not enter bid competitions with industry. Its viability as a systems engineering organization is based on the quality and cost of work it performs. It is subject to all the market forces that govern the establishment of a quality work force at competitive costs. To attract a quality staff, the work must be challenging and rewarding, the facilities matched to accomplishing the work, and the salaries and benefits competitive with industry. To be competitive with other sources of systems engineering, the work must be well done and the costs as low or lower than potential alternatives for equivalent work.

Although this book emphasizes MITRE's systems engineering activities, it also fully recognizes the crucial roles of government and industry in the successful acquisition and operation of C^3I systems. Government personnel establish the needs, provide the funding, manage the acquisition programs, and employ the resulting systems to achieve the required operational capabilities. MITRE cannot accomplish these functions. Although expected to help in any way possible and to take the initiative in all technical matters,

the Corporation must avoid even the appearance of usurping the responsibilities of a program director. MITRE strives to be a full partner as part of the program office in carrying out an acquisition program.

Similarly, profit-making industry—not MITRE—provides the actual hardware and software integral to these systems. MITRE has neither the charter nor the resources to provide these things. Without industry, the combination of government and MITRE cannot provide the needed capabilities. The Corporation's role is to work between government and industry as a catalyst, an honest broker, in helping to achieve the capability. When performing effectively in that role, its efforts are as helpful to industry as they are to the government. MITRE is not in the business of harassing industry, but rather strives to help government and industry achieve the needed capabilities.

The environment within which military and other government C^3I systems are defined, acquired, and operated is challenging. It is competitive—each military program vies with others for resources, and the military competes with social services and other important government needs. It is large, complex, and extremely dynamic. Many people in important positions are involved, each with strong opinions and in a position to affect significantly the course of the program. The people in these positions tend to change quite often, and the new people often have different opinions than their predecessors. Technology advances while enemy capabilities and threats vary over time. New and modified operational requirements may arise. All these factors contribute to an extremely complicated management challenge for the government acquisition program director and hence for MITRE in providing advice to the director and the integrated product team. An additional complication of the environment is that every new system must interoperate with other existing and planned systems, each of them equally subject to the environment, if an effective military mission capability is to result. MITRE's experience on so many of these systems is especially valuable in this regard.

To be effective, the MITRE systems engineering team must fully understand the environment—the existing systems, all of the planned systems with which the one they are working on must interface, the status of each of these systems, all of the players that can affect the program and direction they may have given, resources available to the program director, the status of industry and government efforts on the program, developing technology that may be applicable, and the evolution of the enemy threat to the planned capability. Thorough understanding of that evolution, gained through many years experience in analyzing enemy systems for ESC and other government agencies, is another unique MITRE advantage in systems engineering of C^3I systems.

The day-to-day MITRE systems engineering job is to be conversant with the military capability that the acquisition program is to help provide, continuously conscious of the environment within which the program is taking place, and constantly assessing what needs to be done to maximize the probability of achieving the required capability on a reasonable schedule and at a reasonable cost. The MITRE team must take the initiative to advise the integrated product team on any actions required by the Corporation or by another team member to achieve that goal. The advice must be forthright, implementable, and above all, correct. MITRE must be careful to weed out the trivia and to emphasize actions important to the success of the program.

As required by ESCR 80-1, on each project, MITRE must deliver the systems engineering products called for in the contract covering the work. However, as programs evolve and the program director and the MITRE project leader agree a change in the products is necessary, the Corporation is able to quickly redirect its staff to match the program dynamics. This is another unique MITRE advantage in the systems engineering role.

MITRE's staff takes a broad systems view, but each is expert in one or more of the technologies, operational mission areas, or management tools relevant to C^3I system engineering. The technical

staff gain this knowledge and experience in various ways. Technical training; experience on systems engineering projects; interactions with experts both in MITRE and elsewhere, including user command personnel; working at operating locations; participating in test activities at operational sites and in various other test locations, including contractor plants; all help to increase staff capabilities. MITRE's staff, like all professionals, sometimes needs special facilities to derive the answers to important technical questions. These might include simulation programs, test facilities, or computer analysis programs. The technical questions that must be answered should be identified first, and only then the facilities that might be required to answer them.

MITRE's specific systems engineering activities for each phase of an acquisition program are reviewed in Chapter 2. They include analysis work prior to the initiation of a new program, activities during the acquisition program, and participation in the subsequent evaluation of how well the resulting system satisfies the user command requirements. In addition, other chapters address MITRE's work on specialty areas that are important to all effective C^3I systems. These include interoperability with other systems, reliability and maintainability, system availability, physical and electronic survivability, training, system performance monitoring, supportability, testing, and provision of GFE. Some of the lessons MITRE learned in these areas are also covered.

MITRE believes a program was a success if the government achieved the best capability possible for the time and money invested. It is always a feeling of great pride and satisfaction when the systems one has worked so hard to perfect perform well in helping to accomplish the intended operational mission. MITRE's systems engineering work provides ample opportunity for this professional reward. The corporate role and the associated responsibility are the challenge and the satisfaction that the staff enjoys. They are the reasons that dedicated professionals work at MITRE—the challenge of the responsibility and the chance to do

The MITRE Corporation, Bedford, Massachusetts

something significant toward the achievement of important national capabilities.

As systems engineer, MITRE is prepared to take extraordinary steps to help the government achieve required capabilities and often does. At the same time, both the Corporation and the government must observe the rules that govern FFRDCs. MITRE cannot usurp the roles of either government or industry and must studiously avoid even the appearance of a conflict of interest. Only in these ways will the special relationship between MITRE and the government be preserved for future programs of national significance.

MITRE Systems Engineering Documentation and Tools

Much has been learned at MITRE over the last 35 years about the systems engineering of command, control, communications and intelligence (C^3I) systems. That knowledge resides in the experienced MITRE systems engineering staff. It has also been recorded in a very lengthy list of corporate documents. Effective use by the MITRE staff of the information contained in that documentation can significantly improve the Corporation's performance in the systems engineering role. In addition, the existing documentation is a meaningful record of the breadth and depth of the Corporation's systems engineering skills and of the impact those skills have had on the success of Electronic System Center (ESC) acquisition programs. For those reasons, that documentation is worthy of some discussion here.

Clearly, no brief summary can do justice to the thousands of MITRE documents that have been produced. On the other hand, the material cited here is intended to help one understand the scope of MITRE's work in the systems engineering role. Beyond that, by citing a series of specific documents, it is hoped to reinforce a number of key points made in the book. These include the assertion that the MITRE staff is skilled in the technical areas important to C^3I systems

acquisition, that the Corporation applies those skills to the job, and that MITRE technical skills have significant impact on the success of the acquisition programs for which the Corporation has the systems engineering role.

Much of MITRE's documentation is project-specific. It might include a system specification, analysis of test results, study of the impact of a proposed change in requirements, and many other similar papers. However, there is also a body of technical documentation that transcends individual projects. The references in this Appendx include both project-specific and generic material.

Existing MITRE documentation may be obtained through MITRE's Library. Judicious use of this information by the technical staff improves MITRE's performance in the systems engineering role. Library research facilities will help to identify what is available and to retrieve it when necessary. Discussions with MITRE staff experts can facilitate the identification of the important and current documents in any given area. A recent MITRE initiative, called the Software Experience Factory, is collecting MITRE experiences in system and software acquisition, storing them in a central on-line database, and making the database accessible to the staff. This database contains briefings, letters, and memoranda that convey MITRE's lessons learned and information across system acquisition projects.

The Scope of MITRE's Systems Engineering Activities

MITRE's activities as systems engineer for ESC C^3I systems are described in the body of this book. The approach used here is general in nature and uses work on a specific project only to help illustrate particular points. However, a chronicle of MITRE's activities on a specific major systems engineering project is another way to explain what MITRE does and how that work impacts on the C^3I system acquisition program.

One of MITRE's major projects over the last 25 years has been the Airborne Warning and Control System (AWACS). The Corporation has served as systems engineer on the U.S. AWACS project from the beginning of the acquisition in the late 1960s through several major

upgrades to the system. MITRE was also the systems engineer on the NATO and Saudi Arabian AWACS programs. In 1990, the Corporation published a document that recounts its activities with the U.S. AWACS and the initiation of the NATO AWACS program.[1] The document was written by the MITRE technical staff who were the key people in the Corporation's work on the programs; it covers the basic rationale for AWACS and MITRE's work in preparing the system specification. AWACS had to be sold both technically and operationally. Many high level people of varying opinions were involved in program decisions. Could the radar be made to work satisfactorily? Was the resulting capability operationally useful? As described in the paper, MITRE played key roles in establishing positive answers to both of these questions. The Corporation's many contributions to the success of the AWACS program are reviewed in the referenced report.

The AWACS project is an excellent example of the range of MITRE activities as systems engineer for a large C^3I system. It is also a fine example of the impact that MITRE can have on such a system. The Corporation's work was crucial to the Department of Defense (DOD) and congressional decisions affirming that the system would work and that it would be operationally useful. The validity of those decisions has been amply demonstrated many times over the years, but no more dramatically than in the Gulf War.

Producing a report such as the AWACS document described above is a time-consuming and expensive process. For those reasons, not many MITRE papers are specifically intended to describe the range of MITRE activities in the systems engineering role. Another historical example that helps one to understand some of the MITRE culture is provided in a book by J.F. Jacobs.[2]

Normally, each of the MITRE individual project efforts is documented as it takes place. To gain a project-wide appreciation for the

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[1] *MITRE and AWACS: A Systems Engineering Perspective*, The MITRE Corporation, Bedford, MA, 1990.

[2] J.F. Jacobs, *The SAGE Air Defense System, A Personal History*, The MITRE Corporation, Bedford, MA, 1986.

Corporation's work requires a review of many different documents. There is, however, another class of documents that summarizes MITRE's work on major projects. Each year, the Corporation provides awards to MITRE personnel who have worked on a government project that has reached some major milestone or achieved operational status. To compete for these awards, a MITRE project leader must submit a document to management describing MITRE's work on the project and its contribution to the project's success. These documents help illustrate the Corporation's systems engineering work on a project-by-project basis and can be obtained from the respective project leaders.

Although not limited to MITRE's work for the Air Force, a DOD publication summarizes the very broad scope of the Corporation's activities and contributions on DOD programs for 1990 and 1991.[3]

High Impact MITRE Technical Work

The objective of all of MITRE's work, of course, is to have a positive impact on the success of the acquisition projects for which the Corporation has systems engineering responsibility. MITRE's systems engineering work affects a system acquisition program in many ways. In this section, a few of its most significant technical contributions are briefly mentioned. These examples help to illustrate the technical strength of the MITRE staff and the ability of the Corporation to apply that strength to the government's acquisition programs.

MITRE analysis and simulation studies resulted in a major redesign of the AWACS radome and a significant improvement in system performance.[4] MITRE evaluated the compromises between the electromagnetic propagation and aerodynamic requirements of an early Milstar satellite communication aircraft radome.[5] To aid in the design and development of the installation of a Milstar terminal on an

[3] *Application and Use of the Fiscal Year 1990 and Fiscal Year 1991 Reports and Recommendations Provided by the MITRE C³I FFRDC to the Department of Defense,* Office of the Assistant Secretary of Defense (C³I), Washington, D.C.

[4] *MITRE and AWACS: A System Engineering Perspective,* The MITRE Corporation, Bedford, MA, 1990.

[5] B.F. Hubin, *Shape Analysis of the MILSTAR Raytheon ABNCP Radome,* WP 26744, The MITRE Corporation, Bedford, MA, 1986.

aircraft, the Corporation prepared a detailed description of the modifications and interfaces required to the aircraft structure, electrical power, environmental control, and navigation systems.[6]

A critical performance requirement of the Joint Strategic Target Attack Radar System (Joint STARS) radar is detection of slow-moving vehicles. During the early radar design phase, the prime contractor proposed a simplified step scanning approach to beam scanning for moving targets. This approach would have held the antennna at a fixed pointing angle for several radar bursts before moving the antenna a full azimuth beamwidth. MITRE radar system engineers had previously performed a trade-off analysis indicating that a continuous scanning design, in which the antenna is moved a fraction of a beamwidth on every burst, would yield significant improvement in overall performance, especially for low-velocity targets. Thus, the system engineer was able to quickly convince the contractor to accept the continuous scanning design approach.[7] The Corporation's research work identified technical approaches that permit compression of the synthetic aperture radar information sent from the Joint STARS aircraft to the ground.[8] The approach represents a reasonable compromise between reducing the amount of information that must be transmitted and the errors introduced by doing so. MITRE analysis and simulation of several candidate designs for the improved Joint STARS UHF radio system led to a recommendation that the contractor adopted.[9,10]

In performing analyses of radar systems, MITRE needs to determine the characteristics of the targets that the radars will detect. For example, MITRE estimated that the radar cross section of future targets for the

[6] R. Santos et al., *Group A Kit Installation Package*, WP 29871, The MITRE Corporation, Bedford, MA, November 1991.

[7] Radar Design Status (U), memorandum 6460-B1719, The MITRE Corporation, Bedford, MA, 3 October 1986.

[8] B.W. Fam, S.E. Gordon, and J.M Knight, *Synthetic Aperture Radar Compression Using the Multi-State Coding Scheme*, MTR 10998, The MITRE Corporation, Bedford, MA. March 1990.

[9] J. Low and J.A. Sasso, *Joint STARS Cosite Design Technical Evaluation Interim Status Report (U)*, WP 29234, The MITRE Corporation, Bedford, MA, January 1991.

[10] J. Low and J.A. Sasso, *Joint STARS Cosite Technology Evaluation Study – Interim Results (U)*, WP 29745, The MITRE Corporation, Bedford, MA, 31 July 1991.

Advanced Surveillance Tracking Technology (ASTT) system. To perform such analyses, the Corporation has had an ongoing set of projects that bring in new electromagnetic calculation codes and enhance them to allow practical and accurate calculations of the type needed. The codes and methods developed have been documented.[11]

As the radar cross section of airborne targets such as stealth aircraft and cruise missiles becomes increasingly smaller, larger power-aperture products are needed to prevent clutter from interfering with the target. As the power-aperture increases, so does the clutter level. This is particularly true for high pulse-repetition frequency radars, since near-in clutter competes with distant targets. Also, as the receiver aperture is made larger, the susceptibility to jamming increases. Receiving antennas with ultralow sidelobe patterns have been proposed for large phased-array radars to suppress interference signals. However, MITRE identified limitations in these techniques for achieving required interference signal suppressions and developed a flexible end-to-end simulation that can be used to evaluate the capabilities of ASTT adaptive antenna radar designs.[12,13,14] The simulation program enables systems engineers to perform complexity-versus-performance tradeoffs relative to the optimal space-time processing for these implementations.

As part of its support to various DOD over-the-horizon backscatter (OTH-B) radar programs over the past 10 years, MITRE has developed a simulation program (HFRAD) that allows a user to predict the performance of an OTH-B radar under various environmental conditions.[15] This program has been calibrated against real-

[11] D.P. Allen et al., *MSR Project 90880: Target Scattering Year-End Report*, MTR 10640, The MITRE Corporation, Bedford, MA, August 1989.

[12] B.B. Suresh and J.A. Torres, *Advanced Airborne Radar Simulation with Adaptive Antenna Techniques*, Vol. 1, MTR 92B0000058, The MITRE Corporation, Bedford, MA, August 1992.

[13] B.B. Suresh and J.A. Torres, *Airborne Radar Simulation with Adaptive Antenna Techniques*, M 92B00000083, The MITRE Corporation, Bedford, MA, July 1992.

[14] B.B Suresh and J.A. Torres, *Investigation of Some Critical Issues of Space-Time Processing (STP) Affecting Airborne Radar Performance*, MTR 11055, The MITRE Corporation, Bedford, MA, January 1992.

[15] T.J. Elkins, *OTH Radar Performance Evaluation*, MTR 10938, The MITRE Corporation, Bedford, MA, July 1990.

world systems; it has enabled MITRE to analyze the expected performance of OTH-B radars that are being designed, planned for at possible sites, or tested. This capability has allowed the Corporation to quickly address changing threat scenarios and new missions. The evolution, configuration control, and program verification have been continually documented over this period.[16]

MITRE Systems Engineering Information and Techniques State-of-the-Art Surveys

The technologies associated with modern C³I systems are among the most volatile. No field is changing more rapidly than information systems—MITRE's expertise. Staying current in any particular portion of this technology is a significant challenge. In response to that challenge, MITRE technical experts frequently publish surveys of the state of the art in their particular field. Some recent examples include areas such as electronic support measures (ESM) technology,[17] database management systems,[18] display systems,[19] graphics workstations,[20] and three-dimensional graphics techniques.[21] Since the changes taking place are both frequent and significant, there is a continual need to keep this information up to date. The state-of-the-art information provided helps staff members on the various MITRE projects to stay current. The documentation also serves to identify MITRE experts who can be called upon to help as needed.

MITRE Technical Studies

In addition to survey information, MITRE's staff publishes papers to report on the technical results of its work. Sometimes this information is developed in support of a particular acquisition project; at

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[16] T.S. Lee et al., *HFRAD Version 508 Documentation*, Vols. I, II, and III, WP 29834, The MITRE Corporation, Bedford, MA, 1 March 1992.

[17] *A General Survey of ESM Technology*, Vols. I and II, WP 24849, The MITRE Corporation, Bedford, MA, September 1983.

[18] D. Wolfset, *Comparison of Database Management Systems*, WP 28618, The MITRE Corporation, Bedford, MA, January 1990.

[19] *Large Screen Display Technology Survey*, MTR 8907, The MITRE Corporation, Bedford, MA, July 1984.

[20] J.L. Conway, S.J. Frieter, and J.R. Leger, *Super Graphics Work Stations for Real-Time C³ Systems*, MTR 10894, The MITRE Corporation, Bedford, MA, 1990.

[21] D.A. Southard, *Survey of Three-Dimensional Graphics Techniques for C³I Applications*, M89-5, The MITRE Corporation, Bedford, MA, 1989.

other times, it is developed as part of MITRE's Technology Program. In any case, publication of the results is important, since so many different disciplines are common to a large number of C^3I systems. To be efficient, one must apply knowledge gained in one program to others to which it relates. Again, a wide range of subjects is covered, and only a few of them will be cited here.

In an attempt to speed up the process of acquiring needed capabilities, an approach of rapid prototyping has been employed in the last few years. The approach gives the user an early look at what may be provided and thereby improves the communication between user and developer about requirements. It also helps one's understanding of how difficult providing the capability may be and how much it might cost. MITRE has been applying this approach to its early work on new systems. For example, on the Joint Tactical Distribution System (JTIDS), the Corporation has prototyped automated tools for the generation of the many system initialization parameters needed to operate a network. This has had three benefits: it proved that useful, automated tools could be developed; it resulted in a useful capability for early testing; and it led to a refined set of requirements for the acquisition of tools for operational use.[22,23] MITRE also assesses the efficacy of rapid prototyping as part of many projects and documents that experience.[24]

MITRE has been in the forefront of the network communications area for over 20 years. The Corporation holds patents in that area[25] and has been instrumental in the application of both local area and wide area networks to government systems. MITRE continues to exercise its technical leadership in networks through the efforts of the Corporation's Network Center personnel. Some of their publications

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[22] L.E. Daeke, *JTIDS Network Design Computer Aid - Algorithms*, WP 27770, The MITRE Corporation, Bedford, MA, July 1988.

[23] J.J. Hosker, July 1990, *Program Description for the JTIDS Network Design Utility Aid (UTI)*, MTR 10918, The MITRE Corporation, Bedford, MA, July 1990.

[24] *Rapid Prototyping in Systems Development*, M90-27, The MITRE Corporation, Bedford, MA, June 1990.

[25] D.G. Willard et al., United States Patent #3,851,104, U.S. Patent and Trademark Office (Washington, DC: 26 November 1974).

include information on high speed networks[26,27] and on the latest approach to interfacing diverse systems.[28]

Another important aspect of C³I systems is the display facilities through which the operators interface with the remainder of the system. This has always been a technical skill area within MITRE. Recent publications by the MITRE display engineers include those on large screen display technology [29] and requirements, [30] and liquid crystal[31] and virtual reality displays.[32]

Other recent MITRE technical publications of interest to many projects include those in areas such as the use of ESM data with radar information,[33] ESM data fusion,[34] and communications.[35]

MITRE "How-to" Documents

In the techniques area, MITRE experts in various aspects of systems engineering often document their approach to a particular discipline as a way of helping other members of the technical staff to apply the knowledge and experience to a new project. Although providing step-by-step "how-to" explanations for individual systems engineering tasks is outside the scope of this book, it is important to recognize that many such MITRE papers exist and to illustrate that with a few examples.

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[26] R.S. Edelstein and N.L. Meagher, *High Speed Packet Interconnect for Military Systems*, MTR 10968, The MITRE Corporation, Bedford, MA, September 1990.

[27] K.G. Asnani, G.M. Friedman, and P.N. Jean, *High Speed Networking*, M90-38, The MITRE Corporation, Bedford, MA, August 1990.

[28] K.G. Asnani and P.N. Jean, *Government Open Systems Interconnection Profile (GOSIP)*, M90-37, The MITRE Corporation, Bedford, MA, July 1990.

[29] R.J. Blaha and J.M. Kistner, *Large Screen Display Technology Assessment for Military Applications*, WP 28558, The MITRE Corporation, Bedford, MA, 1989.

[30] P.T. Breen, *Functional Requirements for C³I Large Screen Displays*, The MITRE Corporation, Bedford, MA, 1989.

[31] H. Veron, *Evaluation of Liquid Crystal Shutter Three-Dimensional Stereographic Display Technology*, The MITRE Corporation, Bedford, MA, 1989.

[32] H. Veron, *Display Assessment for Virtual Reality*, The MITRE Corporation, Bedford, MA, 1990.

[33] *A Technique for Automatically Correlating ESM Data and Radar Tracks*, MTR 10451, The MITRE Corporation, Bedford, MA, August 1988.

[34] T.M Hart, *An ESM Data Fusion Process for Tracking Mass Raids*, MTR 10456, The MITRE Corporation, Bedford, MA, September 1988.

[35] *Wide Bandwidth HF Digital Receiver Technology*, MTR 10772, The MITRE Corporation, Bedford, MA, August 1990.

Computer security is a complicated technical problem that pervades most modern C^3I systems. It is an area in which the Corporation has achieved a national reputation for excellence. In a MITRE paper on that subject, the authors describe the most recent DOD policies on information security.[36] They go on to explain the potential system vulnerabilities and alternative means for dealing with them, and they describe sources for guidance in implementing proper safeguards. Relevant technology is reviewed and suggestions made for how to address information security in each program phase. Required testing is discussed in some detail. The role that MITRE's Information Security Center is prepared to play on a program, if required, is also reviewed. The document describes the problem, provides suggestions for dealing with it, and offers additional help. It is a good reminder to MITRE project personnel of the importance of computer security and a useful guide on how to deal with it.

Another challenging area that pervades all C^3I systems is software. Software development is labor-intensive and difficult; as a result, planning for software acquisition and reviewing software products are the focus of considerable technical and management time and attention. MITRE has been very active in these attempts to improve the acquisition of software. The Corporation formed a technical center for software and its staff have produced a number of documents related to how to acquire effective software. These include an overview of the relevant government policies, regulations, and standards for software acquisition.[37] The document is used in an in-house training program for MITRE staff members. A related and more detailed paper provides guidance for tailoring the DOD software development standard to a particular system acquisition.[38] Other papers provide guidance in the preparation and review of software requirements, design, and software quality

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[36] D.J. Bodeau and H.G. Goldman, *Information Security in System Acquisition*, M89-46, The MITRE Corporation, Bedford, MA, August 1989.

[37] W.S. Attridge, *Software Acquisition: Policy, Terminology, and Standards*, WP-27265, Rev. 3, The MITRE Corporation, Bedford, MA, March 1990.

[38] W.S. Attridge, *Tailoring DOD-STD-2167A for ESD Procurements*, MTR 10581, The MITRE Corporation, Bedford, MA, May 1989.

control.[39,40,41,42] Other software-related MITRE papers cover such areas as object-oriented programming,[43] computer-aided software engineering (CASE) tools,[44] use of software metrics in evaluating progress in software development,[45] and application of the Software Engineering Exercise as a tool in contractor selection.[46]

The interface between the people operating the system and the system hardware and software is yet another especially important design consideration. MITRE experts in that area have developed an approach to specifying that interface.[47] This approach embodies the experience MITRE has gained with existing systems.

As previously noted, MITRE plays an important role in source selection, a very difficult and sensitive activity. Who wins and who loses is obviously important both to the companies involved and to the eventual achievement of the needed system capability. Because it is so important, MITRE's role in it has been documented[48] and the contents used by the MITRE Institute to train MITRE staff to participate in source selections. Both technical and ethical considerations are included.

MITRE, of course, is involved throughout the development cycle that follows source selection. Capturing the best practices for system engineering is the objective of other MITRE how-to documents, such as one

[39] T.P. Reagan, M.R. Gardner, and J.P. Hustad, *Criteria and Guidelines for Evaluating Software Requirements Specifications*, MTR 8W00122, The MITRE Corporation, Bedford, MA, July 1988.

[40] E.R. Buley, L.J. Moore, and M.F. Owens, *B5 (SRS/IRS) Specification Guidelines*, M88-57, The MITRE Corporation, Bedford, MA, December 1988.

[41] C.M. Byrnes, *Preparations for Ada Software Analysis (U)*, WP 28264, The MITRE Corporation, Bedford, MA, March 1989.

[42] J. Clapp and S.F. Stanten, *Guide to Total Software Quality Control (U)*, MTR 11284, The MITRE Corporation, Bedford, MA, 1991.

[43] *Object Oriented Technology Day Presentations*, MTP 382, The MITRE Corporation, Bedford, MA, April 1990.

[44] C.M. Byrnes, *Computer-Aided Software Engineering Environment (CASE) and Tools Evaluation*, WP 28542, The MITRE Corporation, Bedford, MA, April 1990.

[45] T.H. Goodwin and H.P. Schultz, *An Initial Evaluation of Metrics Reporting on ESD Programs*, WP 27367, The MITRE Corporation, Bedford, MA, May 1987.

[46] H.P. Schultz, *Software Engineering Exercise Guidelines*, M89-32, The MITRE Corporation, Bedford, MA, June 1989.

[47] N.C. Goodwin, *User-System Interface: Designing for Usability*, M88-54, The MITRE Corporation, Bedford, MA, December 1988.

[48] *Source Selection Reference Manual*, M90-95, The MITRE Corporation, Bedford, MA, December 1990.

on partitioning computer software.[49] There are many other examples of MITRE how-to documents. They range from the strictly technical to the more management-oriented tasks. Their judicious use helps to improve the efficiency and effectiveness of MITRE's systems engineering work.

MITRE Systems Engineering Tools

A significant portion of MITRE's work on an acquisition project can be based on the training and experience of its technical staff. However, as in any profession, staying current with the rapidly changing technology and assessing the new technology for potential application to C^3I systems, requires that the MITRE staff perform technical analyses, conduct experiments, make measurements, or carry out simulations. To do such work requires the time and effort of the staff members, as well as the facilities necessary to perform such tasks. As discussed in Chapter 4,
00 this need is, in part, filled by the MITRE Technology Program. However, such work is also often necessary as a part of an acquisition project. This work is referred to as design verification, and the rationale for it is also discussed in Chapter 4. A few examples of the impact of such work are cited here.

MITRE's analysis and computer simulation work on AWACS mentioned above resulted in a redesign of the radome and an important improvement in the system performance. The Corporation's Joint STARS radar evaluation facility was instrumental in the design of a tracking logic for ground targets as they moved, stopped, or were obscured by terrain features.[50,51] This problem is very different from that of tracking aircraft as seen by a platform such as AWACS. The use of a simulation facility enabled MITRE to define an implementable approach. The Corporation's analysis work on Joint STARS simulation models of the data processing and display subsystems

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[49] E.R. Buley and O. Shapiro, *CSCI Selection Guide*, WP 28273, The MITRE Corporation, Bedford, MA, March 1989.

[50] J.H. Galia, *Use of RS1 in Support of REA Experimental Analysis*, WP 28046, The MITRE Corporation, Bedford, MA, September 1988.

[51] J.H. Galia, J.M. Kistner, and J.C. McCabe, *Effects of Extended Radar Revisit Times on Joint STARS Performance with Reduced Visibility*, WP 28003, The MITRE Corporation, Bedford, MA, September 1988.

identified and predicted bottlenecks and shortfalls in processing capacity.[52] Identification of processing shortfalls led to major upgrades in both the main data processing computers and the operator workstations.

As the examples discussed in this Appendix suggest, MITRE documentation helps to illustrate the systems engineering techniques that have proven successful on major C^3I acquisition projects for ESC. MITRE documentation is also a key factor in making the information on the latest information system technology and techniques available to a broad spectrum of its staff. The existing documentation reflects the Corporation's professional approach to its systems engineering responsibilities.

[52] J.H. Galia and E.C. Grund, *IJSS Introduction with E-8C Modeling Results for the MVCF-866 (U)*, WP 92B0000213, The MITRE Corporation, Bedford, MA, May 1992.

Acronym	Definition
AFMC	Air Force Materiel Command
AFSC	Air Force Systems Command
ALRI	Airborne Long Range Radar Input
AWACS	Airborne Warning and Control System
BITE	Built-in Test Equipment
BUIC	Backup Interceptor Control
C^3I	Command, Control, Communications, and Intelligence
CDRL	Contract Data Requirements List
DOD	Department of Defense
ESC	Electronic Systems Center
ESCR	Electronic Systems Center Regulation
ESD	Electronic Systems Division
ESM	Electronic Support Measures
FAR	Federal Acquisition Regulations
FCRC	Federal Contract Research Center
FFRDC	Federally-Funded Research and Development Center
GFE	Government-Furnished Equipment
IV&V	Independent Verification and Validation
Joint STARS	Joint Strategic Target Attack Radar System
JTIDS	Joint Tactical Information Distribution System
MIT	Massachusetts Institute of Technology
MSR	MITRE Sponsored Research
NADGE	NATO Air Defense Ground Environment
NASA	National Aeronautics and Space Administration
NORAD	North American Aerospace Defense Command
OEP	Operational Employment Plan
OMB	Office of Management and Budget
PMD	Program Management Directive
R&D	Research and Development
RFP	Request for Proposal

Acronym	Definition
SAC	Strategic Air Command
SACDIN	Strategic Air Command Digital Information Network
SAGE	Semi-Automatic Ground Environment
SETA	System Engineering Technical Assistance
SOW	Statement of Work
SPD	System Program Director
SPO	System Program Office
TAC	Tactical Air Command
TBS	Training and Battle Simulation
TEMS	Technical Engineering Management Services
TO&P	Technical Objectives and Plans